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FRACTURE AND FATIGUE OF DIFFUSION, ADHESIVE, AND ROLL BONDED AL--ETC(U)

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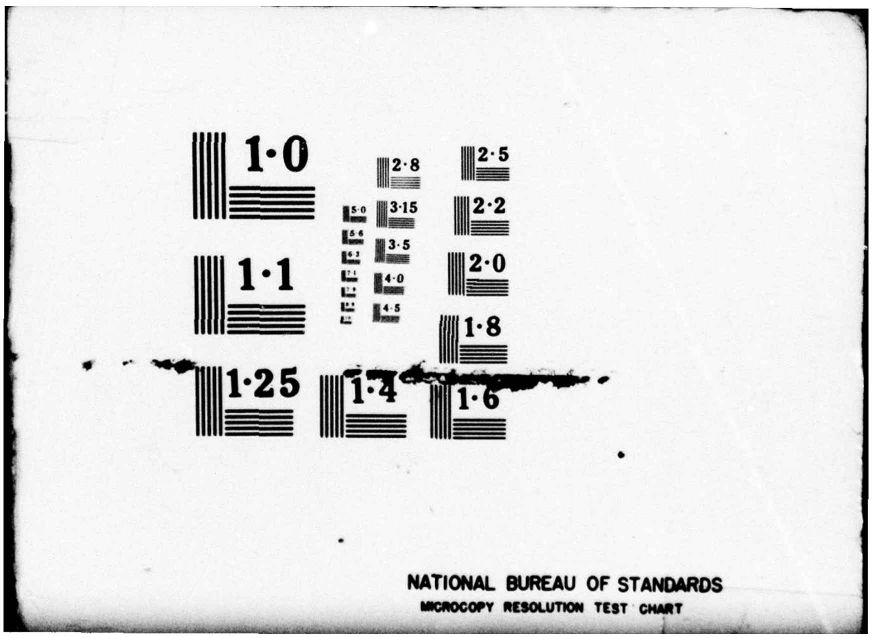
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METAL LAMINATES	DAMAGE TOLERANCE	Ti-6Al-4V
FRACTURE TOUGHNESS	DIFFUSION BONDING	ULTRAHIGH CARBON STEELS
FATIGUE CRACK PROPAGATION	ADHESIVE BONDING	
PERIODIC OVERLOADS	7475 Al	
CRACK ARREST	7075 Al	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The fracture characteristics of twelve different diffusion bonded Al/Al, Ti/Ti and Ultrahigh Carbon Steel/Iron and adhesively bonded Al/Epoxy laminates were evaluated. The effects of periodic overloads on the fatigue crack retardation behavior in a roll bonded Al/Al laminate was also investigated. Specific systems investigated included: diffusion bonded 7475 Al/1100 Al, 7475 Al/6061 Al, 7075 Al/1100 Al, 7075 Al/7072 Al, Ti-6Al-4V/Commercially Pure Ti, and Ultrahigh Carbon Steel/Interstitial Free Iron; adhesively over

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bonded 7475 Al/FM73M and 7075 Al/FM73M; and roll bonded 7475 Al/1100 Al. It was found that all laminates with Al primaries exhibited substantially higher critical fracture toughness in the crack divider orientation than the corresponding baseline monolithic plate alloys. In every case examined, the laminate retained approximately 90% or better of toughness of the individual sheets making up the laminate. Diffusion bonded all-aluminum laminates exhibited greater amounts of subcritical crack growth in the crack divider orientation before fracture than similar adhesively bonded aluminum laminates. Crack divider fatigue crack growth rates in the roll bonded Al/Al laminate subjected to periodic overloads were similar to those of comparable sheet and plate Al at an overload ratio of 1.5. At an overload ratio of 1.8, the laminate's crack growth rate fell between the sheet and plate values, the sheet having the highest rate under these conditions.

PREFACE

This report describes the work performed at Vought Corporation Advanced Technology Center during the period 17 May 1977 to 17 May 1978 on a metals laminate development for structures program. This program was conducted for the Naval Air Systems Command under Contract No. N00019-77-C-0287. The project monitor was Mr. W. T. Highberger, Code AIR-52031D, Naval Air Systems Command, Washington, D. C.

The program was conducted under the supervision of Dr. D. H. Petersen. The principal investigator for this investigation was Dr. R. M. Johnson. Dr. R. D. Goolsby provided much helpful information. Technical support, in many cases of an innovative nature, was provided by Messrs. J. H. Thomas, T. E. Mackie, B. K. Austin, J. B. Middlebrook, J. G. Castillo, R. E. Duval and J. Soroka. Support for laminate fabrication was provided by Mr. J. F. Dolowy, Jr., DWA Composites Specialties, Inc.

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1.0 INTRODUCTION

The application of metal laminates in structural design has seen an increased interest in the past few years, particularly in the aerospace field. Metal laminates are attractive as structural elements because they potentially offer greater reliability, increased life expectancy, and lower cost than conventionally forged and machined components. In particular, the high fracture and fatigue resistance and the crack arrest properties of metal laminates have been the subject of intense investigation.[1-21] These studies have included evaluations of metal/epoxy and metal/metal laminate panels, as well as structural component fabrications using laminated materials. Most of the studies related to aerospace applications have concentrated on metal/epoxy systems primarily because of the potential fabrication cost savings associated with these materials. However, metal/epoxy systems have been limited in primary aerospace structural applications because of uncertainties regarding their use in the presence of hostile environments (e.g., salt water) and their use at elevated temperatures. Accordingly, totally metallic laminate systems should be useful for structures operating under these more severe service conditions.

The present investigation is in its second year and is concerned with development of totally metallic laminates for aerospace structural application. In spite of the numerous studies that have been conducted in the past on both metal/epoxy and metal/metal laminates, insufficient information regarding material, configurational, and processing variables is available for efficient structural design using metal/metal laminates. This study has been directed toward determining the effects of these various parameters on the fracture and fatigue properties of Al/Al, Ti/Al and Ti/Ti laminates.

In the first year,[21] seven different laminate configurations were fabricated by three distinctive processing methods: diffusion bonding, roll bonding and explosive bonding. The materials systems investigated were 7475 Al/1100 Al, 7075 Al/7072 Al, and Ti-6Al-4V/6061 Al. These materials were evaluated for strength, fracture and fatigue properties and compared to sheets and plates of similarly treated monolithic alloys.

The work this second year has been for the most part concentrated on diffusion bonded all aluminum and diffusion bonded all-titanium laminates. Some work on adhesively bonded aluminum has been performed for comparison with the all aluminum systems and a preliminary study was begun on diffusion bonded Ultrahigh Carbon (UHC) Steel/Interstitial Free (IF) Iron laminates. The effects of periodic overloads on fatigue crack propagation in roll bonded Al/Al has been examined also. The specific systems evaluated this year were: diffusion bonded 7475 Al/1100 Al, 7475 Al/6061 Al, 7075 Al/1100 Al, 7075 Al/7072 Al, Ti-6Al-4V Commercially Pure Ti, UHC Steel/IF Iron, adhesively bonded 7475 Al and 7075 Al and roll bonded 7475 Al/1100 Al.

The specific experimental program conducted was designed to isolate the following parameters affecting diffusion bonded metal/metal laminates.

<u>Processing Procedures</u> - The effects of varying surface preparations, bonding times, pressures and temperatures on the integrity of the diffusion bonding were explored. The objective was to obtain clean bond plane interfaces as free as possible from included oxides and which would have good shear strengths and resist premature delamination.

<u>Alloy Type</u> - 7075 Al and 7475 Al (both having very similar chemical composition) were used as primary metals for direct comparisons regarding the use of these two aluminum alloys in laminates. Titanium and ultrahigh carbon steels were also used as primary laminate metals to evaluate their utilities in laminate design.

<u>Interleaf Thickness Effects</u> - Three different interleaf thicknesses were employed in the fabrication of three laminates processed by the same method (diffusion bonding) and having the same metal/metal constitution (7475 Al/1100 Al). Test results from these three laminates allowed comparison of metallurigical,tensile, bond plane shear strengths and fracture properties as a function of interleaf thickness.

The parameters considered in the adhesively bonded laminates included the following:

Improved Adhesives - Higher durability adhesives have been developed in the last few years and surface treatments have been improved. Evaluation of the properties obtainable in laminates formed using the new generation materials and techniques to verify the improvements and to compare to all metal systems was the objective here.

Primary Metal Thickness - The thickness of primary sheets was varied as well as the total thickness of the laminates (using different numbers of layers). Thickness effects on properties could be extracted from appropriate comparisons.

Alloy Type - 7075 Al and 7475 Al were used for direct comparison of these different primary alloy metals in the adhesively bonded laminates. This information also allowed comparison to the all metal systems.

The fracture behavior of these materials were characterized in both crack divider and crack arrest orientations. The metallurgical properties and failure mechanisms were documented using optical metallography, electron probe microanalysis, and scanning electron microscopy.

2.0 EXPERIMENTAL PROCEDURE

2.1 MATERIAL SELECTION

The essential first step in an experimental investigation of metal/metal laminates is the selection of primary and secondary laminae materials and thicknesses. From the numerous investigations that have been conducted on all types of laminar composite systems, it has been noted that the principal factors which affect the fracture resistance of laminates are:

(1) Primary metal properties - strength, toughness, ductility, etc.

(2) Secondary (bonding or interleaf) metal - strength, ductility bonding properties.

(3) Primary metal lamina thickness

(4) Secondary metal (interleaf) thickness

The selections of these metals are described below.

Primary Metal Selection. In the present investigation, aluminum and titanium alloys were considered for application as primary metals, because of the advantageous strength-to-weight ratios of these alloys. Ultrahigh carbon steels developed by Sherby at Stanford were considered for the unique processing potential (superplastic behavior) and anticipated low costs (similar to low alloy steels). Selections of the exact aluminum and titanium alloys were based on fracture toughness vs. thickness characteristics, strength, fatigue resistance, corrosion resistance, and stress corrosion resistance. The alloys selected on this basis were 7075-T6, -T76; 7475-T61, -T761; and recrystallization annealed Ti-6Al-4V. The baseline sheets and plates that were used in this investigation are given in Table 1.

Secondary (Bonding or Interleaf) Selection. The secondary material is considered important primarily because of its effect on bond plane strength, and therefore on the tendency of the primary laminae to fail in a plane stress manner. Failure of the primary laminae under plane stress conditions is necessary to achieve maximum fracture toughness. In all metal laminate preparations, a soft interleaf metal was employed as the secondary or bonding metal. 1100 Al, 6061 Al and 7072 Al were used as interleaf metals in the diffusion bonded Al/Al panels while Commercially Pure Ti was used in the Ti/Ti panel. Interstitial Free (IF)

TABLE I. BASELINE ALUMINUM TITANIUM AND ULTRAHIGH CARBON STEEL ALLOY SHEETS AND PLATES INVESTIGATED.

ALLOY	HEAT TREATMENT CONDITION	NOMINAL THICKNESS mm	(in.)	LOT OR HEAT NUMBER
7475 Al	-T761	2.3	(0.090)	108 - 369
7475 Al	-T7651	13.2	(0.520)	---
7075 Al	-T6	1.27	(0.050)	---
7075 Al	-T76	2.3	(0.090)	---
7075 Al	-T7651	12.7	(0.500)	---
Ti-6Al-4V Titanium	Recrystallization Annealed	3.2	(0.125)	P-1485
Ti-6Al-4V Titanium	Recrystallization Annealed	13.7	(0.550)	P-1742
UHC Steel	Thermomechanically Processed	2.8	(0.11)	---

Iron was employed in the UHC Steel/Iron laminates. In the adhesively bonded Al laminates FM73M supplied by American Cyanamid was used as the secondary material. In the roll bonded 7475 Al, 1100 Al was used as the interleaf metal. Specific secondary thicknesses and laminate configurations are described in Section 2.2.

2.2 LAMINATE SELECTION AND FABRICATION

Diffusion bonding, adhesive bonding and roll bonding were used to fabricate Al/Al, Ti/Ti, UHC Steel/Iron and Al/Epoxy laminates. Thirteen different laminate configurations were evaluated during this study: six diffusion bonded Al/Al laminates, one diffusion bonded Ti/Ti laminate, small diffusion bonded UHC Steel/Iron laminate samples, four adhesively bonded Al/Epoxy laminates and one roll bonded Al/Al laminate. The specific laminate configuations assessed (illustrated schematically in Figure 1) are detailed in Table 2 and are discussed in the following paragraphs.

Diffusion Bonded Laminates. The diffusion bonded laminate panels were fabricated by DWA Composite Specialties, Inc. Five of the Al/Al panels consisted of five layers of 2.3 mm (0.090 in.) thick 7475 Al and 7075 Al sheet interleaved with four layers of 1100 Al or 6061 Al. One panel was made with five layers of 2.5 mm (0.099 in.) thick Alclad 7075 Al. Three panels utilizing 7475 Al primary layers had different 1100 Al interleaf sheet thicknesses [0.05 mm (0.002 in), 0.10 mm (0.004 in.), and 0.25 mm (0.010 in.)]. The other panels had 0.10 mm (0.004 in.) thick interleaves. Special surface preparations were performed prior to the diffusion bonding of the all-aluminum laminates. These preparations consisted of the following: etching of the primary alloy sheets in a solution of one part HNO_3, three parts H_2O with additions of HF to approximately two to four percent, a rinse in H_2O, drying and then a heavy surface abrasion and immediate (within a minute) vacuum bagging. The 7475 Al panels were processed under vacuum for 40 minutes at 496°C (925°F) at 27.6 MPa (4000 psi) pressure. The 7075 Al panels were processed under vacuum for 40 minutes at 488°C (910°F) at 27.6 MPa (4000 psi) pressure. The Ti/Ti laminate consisted of five layers of 3.2 mm (0.125 in) thick recrystallization annealed Ti-6Al-4V titanium alloy sheet interleaved with four layers of 0.13 mm (0.005 in.) Commercially Pure (CP) Ti foil. Following cleaning of the Ti-6Al-4V primary sheets in the same solution described above with rinsing and drying this panel was processed under vacuum for one hour at 871°C (1600°F) at 24.2 MPa (3500 psi) pressure. The area of the Al/Al and Ti/Ti diffusion

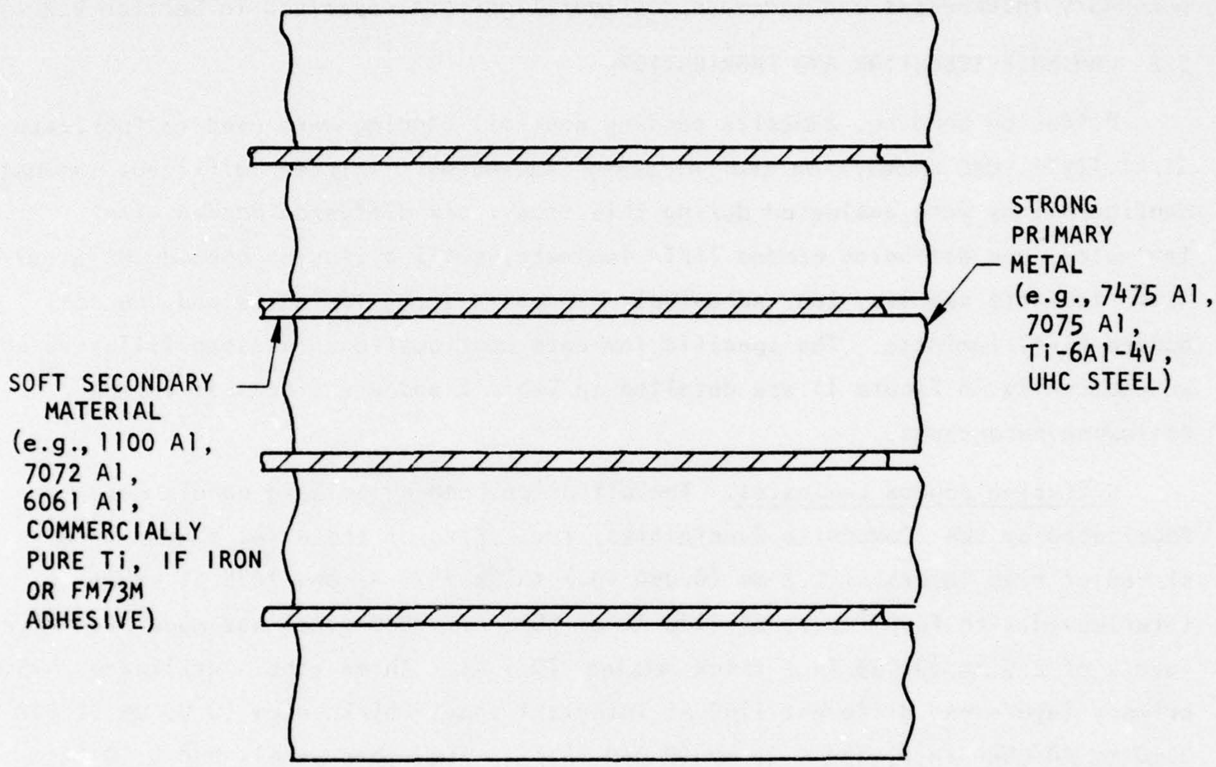


FIGURE 1. SCHEMATIC OF METAL/METAL LAMINATE INVESTIGATED.

TABLE 2. DIFFUSION BONDED ADHESIVE BONDED AND ROLL BONDED Al/Al, Ti/Ti, UHC STEEL/IRON AND Al/EPOXY LAMINATES INVESTIGATED.

LAMINATE PANEL DESIGNATION*	BONDING PROCESS	PRIMARY METAL				SECONDARY MATERIAL				NOMINAL LAMINATE PANEL SIZE mm (in.)
		ALLOY	NUMBER OF LAYERS	LAYER THICKNESS mm	(in.)	ALLOY OR EPOXY	NUMBER OR LAYERS	LAYER THICKNESS mm	(in.)	
DA 4	Diffusion	7475 Al	5	2.3	(0.090)	1100 Al	4	0.05	(0.002)	11.7 x 305 x 305 (0.46 x 12 x 12)
DA 5	Diffusion	7475 Al	5	2.3	(0.090)	1100 Al	4	0.10	(0.004)	11.9 x 305 x 305 (0.47 x 12 x 12)
DA 6	Diffusion	7475 Al	5	2.3	(0.090)	1100 Al	4	0.25	(0.010)	12.5 x 305 x 305 (0.49 x 12 x 12)
DA 7	Diffusion	7475 Al	5	2.3	(0.090)	6061 Al	4	0.10	(0.004)	11.9 x 305 x 305 (0.47 x 12 x 12)
DA 8	Diffusion	7075 Al	5	2.3	(0.090)	1100 Al	4	0.10	(0.004)	11.9 x 305 x 305 (0.47 x 12 x 12)
DA 9	Diffusion	7075 Al Alclad	5	2.5	(0.099)	7072 Al (Alclad Layer)	4	0.10	(0.004)	11.9 x 305 x 305 (0.49 x 12 x 12)
DT 2	Diffusion	Ti-6Al-4V	5	3.2	(0.125)	CPTi	4	0.13	(0.005)	16.4 x 305 x 305 (0.65 x 12 x 12)
DUHC 1	Diffusion	UHC Steel	4	0.80	(0.032)	Iron	3	0.40	(0.016)	6.6 x 38 x 76 (0.26 x 1.5 x 3)
AA 1	Adhesive	7475 Al	5	2.3	(0.090)	FM73M	4	0.13	(0.005)	11.8 x 305 x 305 (0.47 x 12 x 12)
AA 2	Adhesive	7075 Al	9	1.3	(0.050)	FM73M	8	0.13	(0.005)	12.5 x 305 x 305 (0.49 x 12 x 12)
AA 3	Adhesive	7075 Al	3	2.3	(0.090)	FM73M	2	0.13	(0.005)	7.1 x 305 x 305 (0.28 x 12 x 12)
AA 4	Adhesive	7075 Al	5	2.3	(0.090)	FM73M	4	0.13	(0.005)	11.8 x 305 x 305 (0.47 x 12 x 12)
RA 4	Roll	7475 Al	5	2.3	(0.090)	1100 Al	4	0.13	(0.005)	11.9 x 205 x 1120 (0.47 x 12 x 44)

* Panels numbered consecutively from panels investigated in the first year.[21]

bonded panels fabricated was approximately 305 mm x 305 mm (12 in. x 12 in). The Ultrahigh Carbon Steel/Iron laminate samples were bonded for twelve hours at 650°C (1200°F) at 69 MPa (10,000 psi) pressure. The surface preparations consisted of abrading the primary sheets of UHC steel with emery cloth followed by degreasing in acetone. The area of these small samples was approximately 38 mm x 76 mm (1.5 in x 3.0 in).

Adhesively Bonded Laminates. The adhesively bonded Aluminum/Epoxy laminate panels were fabricated by Vought Corporation Advanced Technology Center. One panel consisted of five layers of 2.3 mm (0.090 in) thick 7475 Al, one panel of nine layers of 1.3 mm (0.005 in.) thick 7075 Al and two panels of three and five layers respectively of 2.3 mm (0.090 in.) thick 7075 Al. In every case, the adhesive used was American Cyanamid's FM73M of nominal thickness 0.38·mm (0.015 in.) which produced a secondary layer thickness of approximately 0.13 mm (0.005 in) in the bonded condition. The surface preparation consisted of Vought's Bond Clean (FPL etch) followed by phosphoric acid anodize (Boeing Specification BAC 5555). Adherend surfaces were primed according to manufacturer's specifications using American Cyanamid BR 127 primer. The adhesive was cured at 121°C (250°F) at 0.34 MP (50 psi) for one hour. The area of the adhesively bonded panels was approximately 305 mm x 305 mm (12 in. x 12 in.).

Roll Bonded Laminate Panel. The roll bonded Al/Al laminate panel was fabricated and heat treated by Alcoa Technical Center. The laminate configuration consisted of five layers of 2.3 mm (0.090 in.) 7475 Al sheet interleaved with four layers of 0.13 mm (0.005 in.) 1100 Al sheet. Total size of the laminate was 11.9 mm x 305. mm x 1120 mm (0.47 in. x 12 in. x 44 in.). The final laminate panel was fabricated by initially processing three subpanels and warm rolling these three subpanels into the final configuration. After roll bonding the panel to final dimensions the laminate was heat treated to give -T7651 properties to the primary 7475 Al metal.

2.3 CHEMICAL ANALYSIS, MICROSTRUCTURAL EVALUATION, AND NONDESTRUCTIVE INSPECTION

Chemical Analysis. All primary metal sheets and plates used in this program were analyzed by emission spectroscopy to determine chemical compositions.

Microstructural Evaluation. Baseline metal sheets and plates and laminated panels were examined using a Leitz Ortholux metallograph. Electron probe microanslysis was performed on selected laminates using a Cameca MF 46 analyzer.

Nondestructive Inspection. All laminates with the exception of UHC Steel/Iron laminates were inspected using ultrasonic C-scan.

2.4 MECHANICAL TESTING

2.4.1 Tension Tests

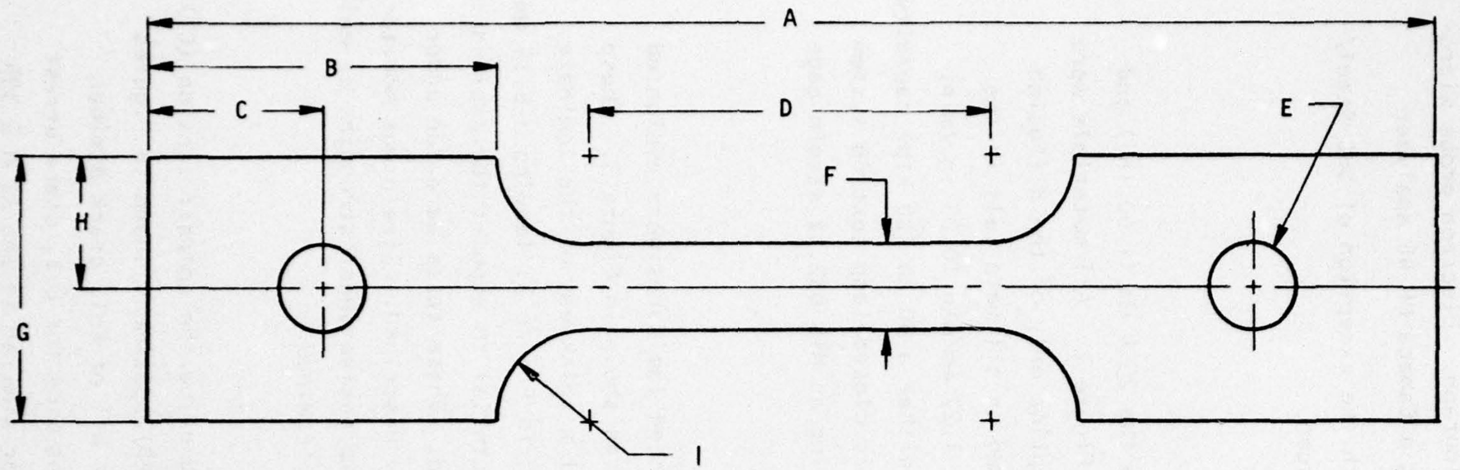
The tension tests were performed using the 25.4 mm (1.00 in.) and 50.8 mm (2.00 in.) gage length specimens shown in Figure 2. All materials were evaluated using the 25.4 mm specimen with the exception only of the diffusion bonded laminate DT2. Duplicate tests were performed on all materials in the longitudinal orientation. These tests were run at 1.27 mm/min (0.05 in./min) at room temperature. Testing was accomplished on either a 90 kN (20 kip) capacity CGS or 450 kN (100 kip) capacity MTS servo-hydraulic closed-loop testing system under stroke control. Elongation was monitored using an MTS 632.12 strain gage extensometer.

2.4.2 Compressive Bond Plane Shear Tests

The bond plane shear strengths of selected laminates were evaluated utilizing a compact compressive lap shear specimen as shown in Figure 3. These samples were 25.4 mm (1.00 in.) x 25.4 mm (1.00 in) x thickness of the laminate. They were slit through the primary layers, as shown in Figure 3, leaving a 6.35 mm (0.25 in) x 25.4 mm (1.00 in.) area of interleaf material to support the applied compressive loads. Triplicate tests were performed. These tests were run under the same conditions as the tensile tests previously described. Strain was monitored by cross head movement. The 0.2% offset yield compressive shear strengths as well as the ultimate compressive shear strengths were determined.

2.4.3 Fracture Tests

Fracture toughness tests were performed using the compact tension (CT), single-edge-notched (SEN), and three point bend (TPB) specimens shown in Figures 4, 5 and 6. The SEN and CT specimens were used for all of L-T, crack divider orientation tests (Figure 7). The TPB specimen was used for L-S, crack arrest tests (Figure 7). Testing was performed in a manner similar to the ASTM E 399 test method for compact tension and three point bend specimens,[22] and to the procedure outlined in the Damage Tolerant Design Handbook.[23] The specimens were fatigue



SPECIMEN GAGE LENGTH mm (in.)	DIMENSION mm (in.) A	B	C	D	E	F	G	H	I
25.4 (1.00)	82.6 (3.25)	19.0 (0.75)	9.5 (0.38)	31.8 (1.25)	6.4 (0.25)	3.2 (0.12)	19.0 (0.75)	9.5 (0.38)	6.4 (0.25)
50.8 (2.00)	184 (7.25)	50.8 (2.00)	25.4 (1.00)	57.2 (2.25)	12.7 (0.50)	12.7 (0.50)	38.1 (1.50)	19.0 (0.75)	12.7 (0.50)

FIGURE 2. 25.4 mm (1.00 in.) AND 50.8 mm (2.00 in.) GAGE LENGTH TENSILE SPECIMENS.

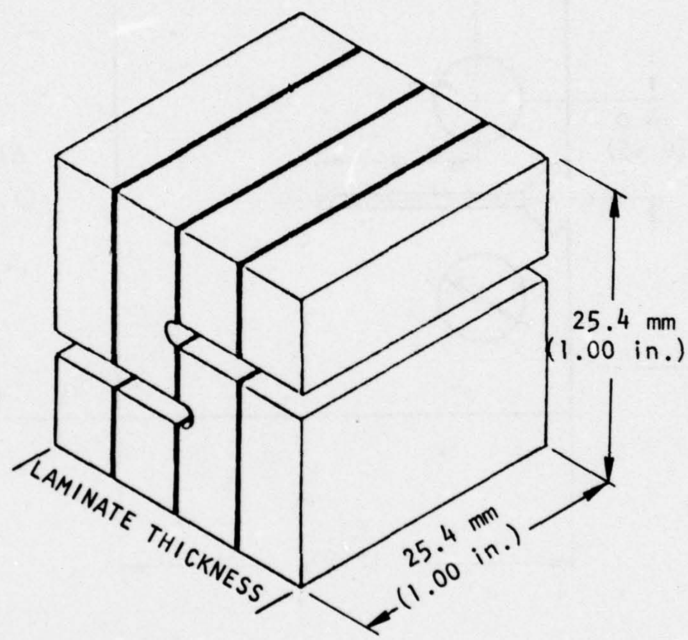
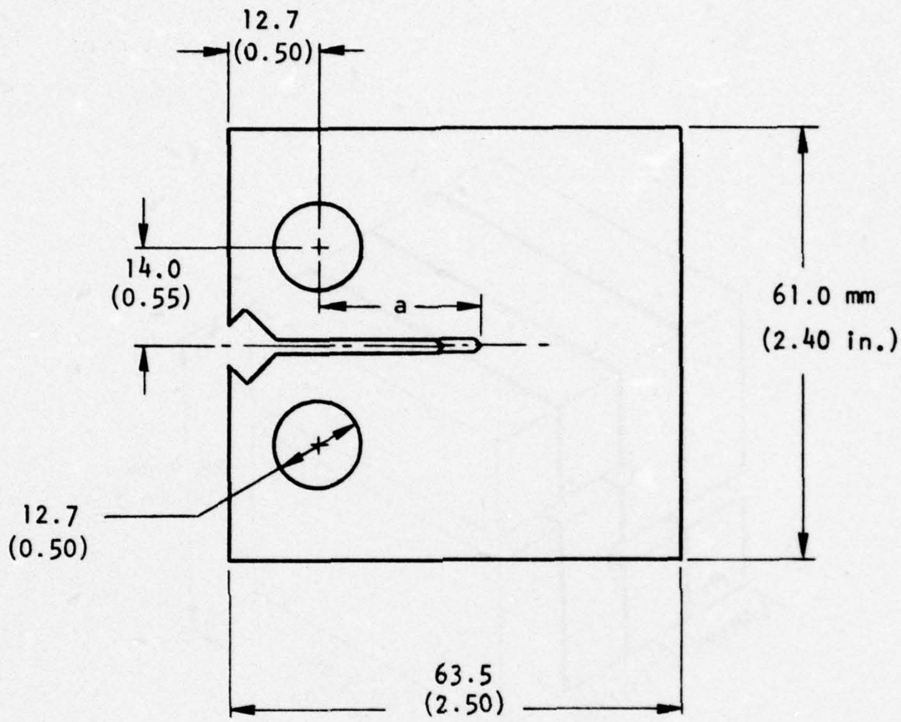


FIGURE 3. COMPACT COMPRESSIVE LAP SHEAR SPECIMEN.

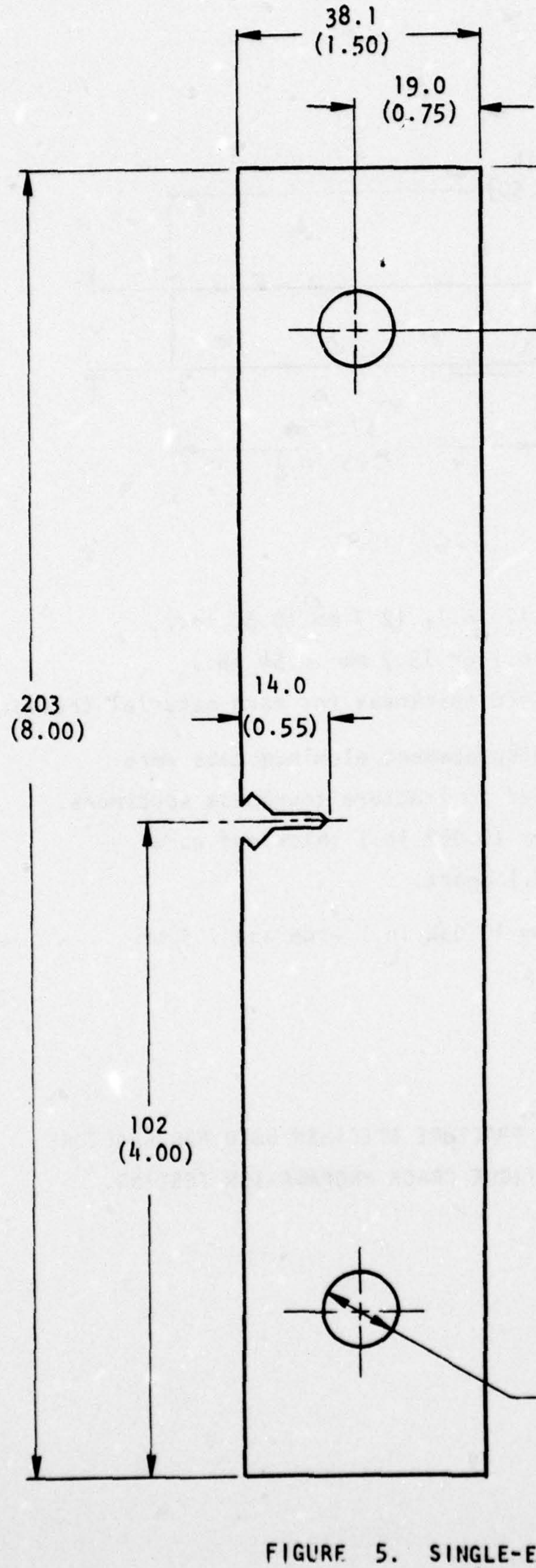


Notes: (1) Knife edges at notch opening are 5.1 mm (0.20 in.) apart.

(2) Notch is chevron shaped at tip and is 1.6 mm (0.063 in.) wide.

(3) a = 22.9 mm (0.90 in.) for fracture toughness test specimens.
a = 10.2 mm (0.40 in.) for fatigue crack propagation test specimens.

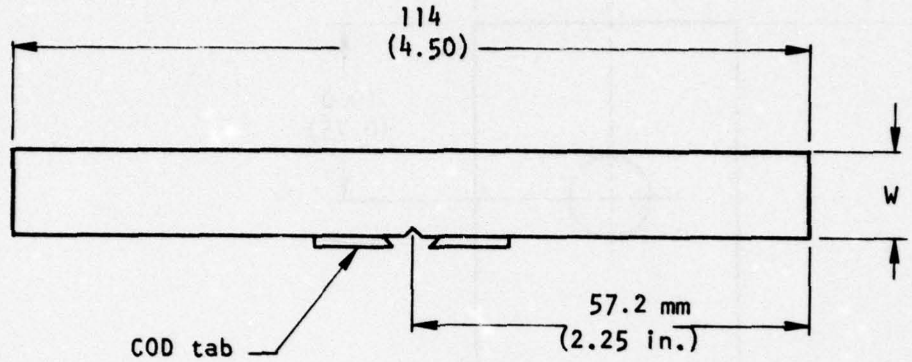
FIGURE 4. COMPACT TENSION FRACTURE SPECIMEN USED FOR FRACTURE TOUGHNESS AND FATIGUE CRACK PROPAGATION TESTING.



Notes: (1) Knife edges at notch opening are 5.1 mm (0.20 in.) apart.

(2) Notch is chevron shaped at tip and is 1.6 mm (0.063 in.) wide.

FIGURE 5. SINGLE-EDGE-NOTCHED FRACTURE SPECIMEN.

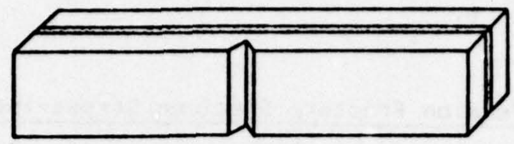


Notes: (1) W = 11.9 mm (0.47 in.), 12.7 mm (0.50 in.), 13.2 mm (0.52 in.) or 13.7 mm (0.54 in.), depending on plate thickness for each material tested.

(2) Crack-opening-displacement aluminum tabs were adhesively bonded to fracture toughness specimens. Tabs were 1.6 mm (0.062 in.) thick and were 5.1 mm (0.20 in.) apart.

(3) Notch was 0.8 mm (0.032 in.) wide and 1.3 mm (0.050 in.) deep.

FIGURE 6. THREE POINT BEND FRACTURE SPECIMEN USED FOR FRACTURE TOUGHNESS AND FATIGUE CRACK PROPAGATION TESTING.



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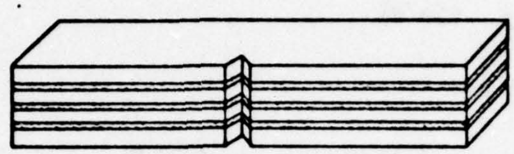


(b)

FIGURE 7. (a) CRACK ARREST AND
(b) CRACK DIVIDER LAMINATE ORIENTATIONS.

precracked at 10 Hz and subsequently tested to failure using a loading rate within the ASTM recommended range. A double cantilever crack-opening-displacement (COD) gage similar to that developed by Fisher, et al.[24] was used to monitor crack length during testing. Load and crack-opening-displacement were recorded on an X-Y recorder for all tests. These tests were run in triplicate at room temperature on either the CGS or MTS system described earlier.

Pertinent crack lengths relative to the load/crack-opening-displacement failure curves were determined using experimentally derived COD compliance calibrations. These COD compliance calibrations were determined for each specimen configuration (CT, SEN, and TPB, including a calibration for three different values of W for the TPB specimen).

The following fracture toughness parameters were determined for specimens tested in this study:

K_Q - conditional fracture toughness, determined by the 5% offset method described in ASTM E 399-74

K_{app} - apparent fracture toughness, evaluated using maximum failure load and the original crack length

K_c - critical fracture toughness, evaluated using maximum failure load and the crack length at failure

Crack growth resistance "R-curves"[25] were also determined for selected laminates.

Compact Tension Fracture Specimen Stress-Intensity Determinations. Fracture toughness values determined from compact tension specimen tests were calculated using the following relation[22]:

$$K = \frac{P}{BW^{1/2}} \quad f(a/W) \tag{1}$$

where f(a/W) is given by:

$$f\left(\frac{a}{W}\right) = 29.6 \left(\frac{a}{W}\right)^{1/2} - 185.5\left(\frac{a}{W}\right)^{3/2} + 655.7\left(\frac{a}{W}\right)^{5/2} - 1017.0\left(\frac{a}{W}\right)^{7/2} + 638.9\left(\frac{a}{W}\right)^{9/2}$$

and

K - stress-intensity factor

P - load

B - specimen thickness

W - specimen width

a - specimen crack length

Single-Edge-Notched Fracture Specimen Stress-Intensity Determinations. Fracture toughness values determined from SEN specimen tests were evaluated using the following expression[26]:

$$K = \frac{Pa^{1/2}}{BW} \quad f(a/W) \tag{2}$$

where f(a/W) is given by:

$$f(a/W) = 1.99 - 0.41\left(\frac{a}{W}\right) + 18.70\left(\frac{a}{W}\right)^2 - 38.48\left(\frac{a}{W}\right)^3 + 53.85\left(\frac{a}{W}\right)^4$$

and

K - stress-intensity factor

P - load

a - specimen crack length

B - specimen thickness

W - specimen width

Three Point Bend Fracture Specimen Stress-Intensity Determinations. Three point bend specimens used in this investigation had span-to-width ratios, S/W, of approximately 8. Fracture toughness values determined using TPB specimens were evaluated from the following expression[26,27]:

$$K = \frac{6Ma^{1/2}}{BW^2} \quad f(a/W) \tag{3}$$

where f(a/W) is given by:

$$f(a/W) = 1.96 - 2.75\left(\frac{a}{W}\right) + 13.66\left(\frac{a}{W}\right)^2 - 23.98\left(\frac{a}{W}\right)^3 + 25.22\left(\frac{a}{W}\right)^4$$

and

K - stress-intensity factor

M - applied bending moment

a - specimen crack length

B - specimen thickness

W - specimen depth

2.4.4 Fatigue Tests

Fatigue crack propagation tests were performed using the L-T, crack divider orientation compact tension fracture specimen (Figure 4) and the L-S, crack arrest orientation three point bend fracture specimen (Figure 6). Periodic overload effects were examined in the crack divider roll bonded specimens. These tests were performed in a manner similar to the procedures recommended by the ASTM Task Group E24.04.01 on Fatigue Crack Growth Rate Testing.[28] Tests were conducted on either the CGS or MTS closed-loop testing systems described in Section 2.4.1. These tests were conducted at room temperature at 10 Hz under load control. All tests were run at R = 0.1. Overload ratios of 1.5 and 1.8 were used where these ratios equal the overload divided by the maximum load in the normal fatigue cycle. Crack lengths were measured using a 40X traveling microscope. A minimum of three specimens were tested for each material to arrive at a final crack growth rate (da/dN) vs. stress-intensity

factor range (ΔK) curve. Crack propagation rates were determined using the secant method. Stress-intensity factor ranges for compact tension specimens were determined using the following expression[29,30]:

$$\Delta K = \frac{\Delta P}{BW^{1/2}} \quad f(\alpha) \tag{4}$$

where $f(\alpha)$ is given by:

$$f(\alpha) = \frac{(2 + \alpha)}{(1 - \alpha)^{3/2}} \left(0.866 + 4.64\,\alpha - 13.32\,\alpha^2 + 14.72\,\alpha^3 - 5.60\,\alpha^4 \right)$$

and:

ΔK - stress-intensity factor range

ΔP - $P_{max} - P_{min}$

P_{max} - maximum load

P_{min} - minimum load

α - a/W

a - specimen crack length

W - specimen width

B - specimen thickness

Stress-intensity factor ranges for three point bend specimens were determined using Equation 3, Section 2.4.2.

2.5 FRACTOGRAPHY

The fracture surfaces were examined using an optical metallograph and a Cambridge scanning electron microscope.

3.0 RESULTS AND DISCUSSION

3.1 CHARACTERIZATION OF BASELINE ALUMINUM AND TITANIUM ALLOYS

Primary sheet and monolithic plate alloys used in this investigation were characterized with respect to chemical composition, tensile properties, fracture properties and fatigue properties, so that comparisons could be made with properties of the laminated panels. For the thirteen laminates listed in Table 2, corresponding monolithic plate and single layer sheet alloys were tested with the exception of the UHC steel for which plate has not become available. The chemical analyses of all the principal aluminum, titanium and ultrahigh carbon steel alloys used in this investigation are given in Tables 3, 4 and 5 respectively.

<u>Tensile Properties</u>. The tensile properties of baseline 2.3 mm (0.090 in.) 7475-T751 Al, 7475-T61 and 7075-T76 Al sheet, 12.7 mm (0.500 in.) 7075-T7651 Al plate, 7475-T651, and 13.2 mm (0.520 in.) 7475-T7651 Al plate are given in Table 6. These properties were determined using the 50.8 mm (2.00 in.) gage length tensile specimen configuration illustrated in Figure 3. The values given in the table for 7475-T61 and -T651 were obtained from the literature [31] and should be considered minimum values.

The tensile properties of the baseline 3.2 mm (0.125 in.) Ti-6Al-4V alloy sheet and 14.0 mm (0.550 in.) Ti-6Al-4V alloy plate are given in Table 7. The tensile properties shown were determined using the 25.4 mm (1.00 in.) gage length tensile specimen illustrated in Figure 3. The heat treatment is comparable to the treatment given the laminated Ti-6Al-4V/CPTi DT2 panel during bonding.

The tensile properties for the ultrahigh carbon steel sheet are given in Table 8.

<u>Fracture Toughness Properties</u>. The L-T orientation fracture toughness values of the baseline 2.3 mm (0.090 in.) 7475-T761 Al, 7075-T76 Al and 7075-T6 sheet, 12.7 mm (0.500 in.) 7075-T7651 Al plate, and 13.2 mm (0.520 in.) 7475-T7651 Al plate are given in Table 9. Fracture tests on the 13.2 mm (0.520 in.) 7475-T7651 Al plate were conducted on specimens with a thickness of 11.9 mm (0.470 in.), so that these specimens would be of the same dimensions as comparable 7475 Al/1100 Al laminate specimens. The 38.1 mm (1.50 in.) wide single-

TABLE 3. CHEMICAL ANALYSES OF ALUMINUM ALLOYS.

ALLOY	NOMINAL THICKNESS mm	(in.)	LOT NUMBER	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
7475 Sheet	2.3	(0.090)	108-369	0.04	0.08	1.37	0.00	2.33	0.22	5.64	0.03	Bal.
7475 Primary Roll Bonded Alloy	2.3	(0.090)	356891	0.05	0.06	1.41	0.00	2.57	0.20	5.63	0.03	Bal.
7475 Plate	13.2	(0.520)	---	0.04	0.06	1.42	0.00	2.34	0.20	5.65	0.03	Bal.
7075 Sheet	2.3	(0.090)	212251	0.09	0.24	1.43	0.05	2.74	0.20	5.71	0.02	Bal.
7075 Alclad Sheet (Primary Metal)	2.5	(0.099)	249231	0.09	0.21	1.29	0.03	2.62	0.20	5.64	0.02	Bal.
7075 Plate	12.7	(0.500)	---	0.07	0.24	1.42	0.03	2.44	0.20	5.56	0.04	Bal.

* Chemical analysis given in weight percent.

TABLE 4. CHEMICAL ANALYSES OF Ti-6Al-4V TITANIUM ALLOYS.

ALLOY	NOMINAL THICKNESS mm (in.)	HEAT NUMBER	C	Fe	N	Al	V	H	O	Ti
Ti-6Al-4V Titanium Sheet	3.2 (0.125)	P1485	0.016	0.14	0.016	6.3	4.3	0.011	0.13	Bal.
Ti-6Al-4V Titanium Plate	13.7 (0.550)	P1742	0.017	0.12	0.009	5.8	4.0	0.007	0.11	Bal.

* Chemical analysis is given in weight percent.

TABLE 5. CHEMICAL ANALYSIS OF ULTRAHIGH CARBON STEEL.

ALLOY	NOMINAL THICKNESS mm (in.)	C	Mn	Si	V	S	P	Cr	Ni	Cu	Ti	Fe
UHC Steel	2.8 (0.11)	1.37	1.04	0.22	0.12	0.005	0.01	0.03	0.07	0.01	0.01	Bal

* Chemical analysis is given in weight percent.

TABLE 6.

AVERAGE TENSILE PROPERTIES OF 7475 AND 7075 ALUMINUM ALLOY SHEET AND PLATE.

ALLOY AND TEMPER	NOMINAL THICKNESS		0.2% YIELD STRENGTH		ULTIMATE STRENGTH		% ELONGATION
	mm	(in.)	MPa	(ksi)	MPa	(ksi)	
7475-T761 Al	2.3	(0.090)	468	(67.9)	514	(74.5)	13.1
7475-T7651 Al	13.2	(0.520)	474	(68.8)	522	(75.7)	16.6
7475-T61 Al*	2.3	(0.090)	441	(64)	517	(75)	9
7475-T651 Al*	12.7	(0.500)	469	(68)	538	(78)	8
7075-T76 Al	2.3	(0.090)	479	(69.4)	538	(77.9)	12.0
7075-T7651 Al	12.7	(0.500)	478	(69.3)	530	(76.8)	15.1
7075-T6 Al	2.3	(0.090)	545	(79.1)	587	(85.1)	13.6
7075-T651 Al	12.7	(0.500)	478	(69.3)	530	(76.8)	15.1

* Minimum Values from Alcoa Green Letter.[31]

TABLE 7.
AVERAGE TENSILE PROPERTIES OF Ti-6Al-4V TITANIUM ALLOY SHEET AND PLATE.

ALLOY	HEAT TREATMENT	NOMINAL THICKNESS		0.2% YIELD STRENGTH		ULTIMATE STRENGTH		% ELONGATION
		mm	(in.)	MPa	(ksi)	MPa	(ksi)	
Ti-6Al-4V Sheet	Recrystallization Annealed + 1 Hr. @ 871°C (1600°F)	3.2	(0.125)	924	(134)	993	(144)	9.3
Ti-6Al-4V Plate	Recrystallization Annealed + 1 Hr. @ 871°C (1600°F)	14.0	(0.550)	876	(127)	945	(137)	10.5

TABLE 8.
TENSILE PROPERTIES OF ULTRAHIGH CARBON STEEL SHEET

ALLOY	HEAT TREATMENT	NOMINAL THICKNESS		0.2% YIELD STRENGTH		ULTIMATE STRENGTH		% ELONGATION
		mm	(in.)	MPa	(ksi)	MPa	(ksi)	
1.4% C UHC Steel Sheet	As Thermo-mechanically Processed	2.8	(0.110)	786	(114)	924	(134)	11.3

TABLE 9. L-T ORIENTATION AVERAGE FRACTURE TOUGHNESS VALUES OF 7475 AND 7075 ALUMINUM SHEET AND PLATE.

ALLOY AND TEMPER	NOMINAL THICKNESS mm (in.)	SPECIMEN TYPE*	CONDITIONAL FRACTURE TOUGHNESS, K_Q MPa$\sqrt{m}$	(ksi $\sqrt{in.}$)	APPARENT FRACTURE TOUGHNESS, K_{app} MPa $\sqrt{m}$	(ksi $\sqrt{in.}$)	CRITICAL FRACTURE TOUGHNESS, K_c MPa $\sqrt{m}$	(ksi $\sqrt{in.}$)
7475-T761 Al	2.3 (0.090)	SEN	37.8	(34.4)	65.0	(59.1)	90.1	(82.0)
7475-T7651 Al	11.9 (0.470)**	SEN	52.4	(47.6)	60.4	(54.9)	66.3	(60.3)
		CT	49.6	(45.1)	57.7	(52.5)	65.2	(59.2)
7475-T61 Al***	-	SEN	-		-		104	(95)
7475-T651 Al***	-	SEN	-		-		44	(40)
7075-T76 Al	2.3 (0.090)	SEN	32.0	(29.1)	50.9	(46.3)	63.7	(57.9)
7075-T7651 Al	12.7 (0.500)	SEN	34.2	(31.1)	35.0	(31.9)	44.0	(40.0)
7075-T6 Al	2.3 (0.090)	SEN	28.4	(25.8)	46.9	(42.7)	58.7	(53.4)
7075-T6 Al	1.3 (0.090)	SEN	39.5	(36.0)	54.7	(49.8)	66.6	(60.6)
7075-T651 Al***	-	SEN	-		-		29	(26)

* SEN - Single Edge Notched Fracture Specimen; CT - Compact Tension Fracture Specimen.

** 7475-T7651 Al 11.9mm (0.47 in.) thick specimens were machined from 13.2 mm (0.52 in.) plate.

*** Average Values For Sheet and Plate From Alcoa Green Letter.[31]

edge-notched specimen (Figure 5) was used for all fracture tests with the exception only of the 11.9 mm (0.470 in.) thick 7475-T7651 Al plate alloy, where additional compact tension (Figure 4) fracture tests were also conducted. Average values from three tests of conditional fracture toughness (K_Q), apparent fracture toughness (K_{app}), and critical fracture toughness (K_c) have all been tabulated in Table 9. Also included are average values of K_c for 7475-T61 sheet and 7475-T651 and 7075-T651 plate taken from the literature.[31]

The fracture values of the sheet alloys given in Table 9 are not directly comparable to most fracture values listed in such references as the Damage Tolerant Design Handbook[23] because of the small width of the specimens used for tests in this investigation. It was necessary to use small specimens in this program due to the limited quantities of laminate panel material available for testing. However, data for the 7475 Al and 7075 Al sheet does seem to compare well with data Wygonik[23] determined for 76.2 mm (3.0 in.) wide fracture specimens. Complete K_Q, K_{app}, and K_c data for the thick 7475 Al and 7075 Al plates were not available for comparison. The results of Table 9 show that 7475 Al possesses significantly higher fracture toughness than 7075 Al, as has been noted previously.[31-33]

Originally,[21] fracture toughness testing was performed using SEN samples. Additional tests of 7475 Al plate were conducted using CT samples, since CT samples were employed for fatigue crack propagation studies. As can be seen from Table 9, no significant differences were noted in the fracture toughness values for the SEN and CT specimen configurations. Accordingly, subsequent testing on laminates has been performed using CT samples because of the greater material economy afforded by use of these smaller test samples.

The L-T orientation fracture properties of the baseline 3.2 mm (0.125 in.) Ti-6Al-4V alloy sheet and 14 mm (0.550 in.) Ti-6Al-4V alloy plate are given in Table 10. K_Q, K_{app} and K_c values were determined for both sheet and plate material having the same heat treatment history as the laminate fabricated from the sheet. This heat treatment involved an additional hour at 871°C(1600°F) with air cooling (the diffusion bonding condition employed in the laminate processing) on the recrystallization annealed sheet and plate. The recrystallization annealing treatment itself consisted of one hour at 949°C (1740°F), air cool and

TABLE 10. L-T ORIENTATION FRACTURE TOUGHNESS OF Ti-6Al-4V TITANIUM ALLOY SHEET AND PLATE.

ALLOY	NOMINAL THICKNESS mm (in.)	HEAT TREATMENT	SPECIMEN TYPE*	CONDITIONAL FRACTURE TOUGHNESS, K_Q MPa$\sqrt{m}$	(ksi$\sqrt{in.}$)	APPARENT FRACTURE TOUGHNESS, K_{app} MPa$\sqrt{m}$	(ksi$\sqrt{in.}$)	CRITICAL FRACTURE TOUGHNESS, K_c MPa$\sqrt{m}$	(ksi$\sqrt{in.}$)
Ti-6Al-4V Sheet	3.2 (0.125)	Recrystallization Annealed + 1 Hr. @ 871°C (1600°F)	CT	94.1	(85.6)	106	(96.7)	125	(114)
				96.4	(87.7)	109	(99.5)	127	(116)
				95.0	(86.4)	112	(102)	140	(127)
				Avg. 95.2	(86.6)	109	(99.5)	131	(119)
Ti-6Al-4V	14.0(0.550 in)	Recrystallization Annealed + 1 Hr. @ 871°C (1600°F)	CT	69.9	(63.6)	91.3	(83.1)	136	(124)
				70.8	(64.6)	81.1	(73.8)	127	(116)
				61.7	(56.1)	99.7	(90.7)	144	(131)
				Avg. 67.5	(61.4)	90.7	(82.5)	136	(124)
			TPB	60.1	(54.7)	103	(94.1)	137	(125)
				69.9	(63.6)	105	(95.9)	137	(125)
				70.3	(64.0)	100	(91.0)	129	(117)
				Avg. 66.8	(60.8)	103	(93.7)	134	(122)

*CT - Compact Tension Fracture Specimen; TPB - Three Point Bend Fracture Specimens.

then 30 minutes at 760°C (1400°F) with air cooling. Compact tension fracture and three point bend fracture samples were used for direct comparison to the compact tension and three point bend samples from the laminate.

The ultrahigh carbon steel was in limited supply and only sheet was available. The sheet size was too small to permit fabrication of standard size compact tension samples. Therefore, discussion of this material is deferred to Section 3.5.1.

Fatigue Crack Propagation Properties. Fatigue crack propagation tests with periodic overloads were made on 0.23 mm (0.090 in.) 7475-T761 Al sheet and 11.9 mm (0.470 in.) 7475-T7651 Al plate using the compact tension specimen (Figure 4). The results of these tests are discussed in Section 3.6, where direct comparisons are made to similar tests on laminate panels.

3.2 TENSILE PROPERTIES AND MICROSTRUCTURES OF LAMINATE PANELS

3.2.1 Tensile Properties of Laminate Panels

Prior to sectioning and machining for tensile test specimens, each laminate panel was nondestructively inspected for unbonded areas using ultrasonic C-scan. The following observations were made relative to laminates fabricated by the three different lamination processes:

Diffusion Bonded Laminates - It was found that diffusion bonded 7475 Al/1100 Al laminates DA4, DA5 and DA6 as well as the 7475 Al/6061 Al laminate DA7 and the 7075 Al/1100 Al laminate DA8 showed no unbonded regions. Laminate DA9, 7075 Alclad Al in which the cladding material, 7072 Al, served as the secondary metal, showed unbonded regions about the periphery of the panel but appeared sound otherwise. The diffusion bonded Ti-6Al-4V/CPTi laminate DT2 showed no unbonded region by C-scan inspection. The Ultrahigh Carbon Steel/Iron DUHC 1 laminate samples were too small to be inspected reliably by C-scan.

Adhesively Bonded Laminates - Ultrasonic C-scan inspection of adhesively bonded laminates of 7475 Al and 7075 Al, laminates AA1 through AA4 revealed no unbonded areas.

Roll Bonded Laminate - As reported previously,[21] this laminate was characterized by surface blisters which appeared after heat treatment. The blisters were numerous over the area of the panels and were easily identified visually. Ultrasonic C-scan and subsequent metallographic analysis confirmed that the unbonded areas occurred at the outside primary/secondary bond planes.

Tensile Properties of Diffusion Bonded Al/Al Laminates. Samples from the as-received diffusion bonded 7475 Aluminum laminates DA4, DA5, DA6 and DA7 were heat treated at Vought Corporation Advanced Technology Center to achieve -T651 tensile properties. Other samples from DA5 received heat treatment to the -T7651 condition. These samples were heat treated according to the specifications of Alcoa 467 process for 7475 Al sheet material. No problems with delamination during sample machining, heat treating or stress relief straining were encountered in any of these samples. The diffusion bonded laminates of 7075 Al/1100 Al and the 7075 Alclad Al, DA8 and DA9 respectively, were sectioned into samples prior to heat treatment. During machining, the DA9 samples completely delaminated and were subsequently eliminated from further consideration. No problems were encountered for DA8 and samples were heat treated to achieve the -T651 condition. The tensile properties for laminates DA4 through DA8 are given in Table II. These properties with the exception of laminates DA5 and DA6 are representative of alloys of 7475 Al and 7075 Al similarly heat treated. The two exceptions were apparently inadvertently overaged.

Tensile Properties of Diffusion Bonded Ti-6Al-4V/CPTi Laminate. The diffusion bonded laminate DT2 was bonded by DWA Composite Specialties at 871°C (1600°F) for one hour and air cooled. The laminate was examined in this as-received condition. The tensile properties of this laminate are given in Table 12 and the strength values are representative of similarly treated Ti-6Al-4V alloys. Greater % elongation was observed for the laminate.

Tensile Properties of Diffusion Bonded Ultrahigh Carbon Steel/Interstitial Free Iron Laminate. The diffusion bonded laminate DUHC 1 was bonded at Stanford University at 650°C (1200°F) for 12 hours at 69 MPa (10,000 psi) pressure and tested in the as-received condition. The tensile properties of this

TABLE 11. TENSILE PROPERTIES OF DIFFUSION BONDED 7475 Al/1100 Al, 7475 Al/6061 Al AND 7075 Al/1100 Al LAMINATES.

LAMINATE DESIGNATION	PRIMARY ALLOY AND TEMPER	SECONDARY ALLOY	SECONDARY ALLOY LAYER THICKNESS mm (in.)	0.2% YIELD STRENGTH MPa (ksi)	ULTIMATE STRENGTH MPa (ksi)	% ELONGATION
DA4	7475-T651 Al	1100 Al	0.05 (0.002)	526 (73.3) 465 (67.4) Avg. 495 (71.9)	539 (78.1) 516 (74.9) 528 (76.5)	18.4 17.5 18.0
DA5	7475-T651 Al	1100 Al	0.10 (0.004)	461 (66.9) 450 (65.2) Avg. 456 (66.1)	505 (73.3) 497 (72.1) 501 (72.7)	10.3 10.4 10.4
	7475-T7651 Al	1100 Al	0.10 (0.004)	377 (54.7)	446 (64.7)	15.4
DA6	7475-T651 Al	1100 Al	0.25 (0.010)	452 (65.6) 427 (61.9) Avg. 440 (63.8)	499 (72.4) 498 (72.2) 499 (72.3)	16.6 17.5 17.1
DA7	7475-T651 Al	6061 Al	0.10 (0.004)	471 (68.3) 470 (68.1) Avg. 470 (68.2)	522 (75.7) 517 (75.0) 520 (75.4)	15.7 14.6 15.2
DA8	7075-T651 Al	1100 Al	0.10 (0.004)	496 (71.9)	539 (78.2)	15.0

* Laminates were nominally 11.9 mm (0.47 in.) thick

**Primary alloy (7475 Al or 7075 Al) layers were nominally 2.3 mm (0.090 in.) thick.

TABLE 12. TENSILE PROPERTIES OF DIFFUSION BONDED Ti-6Al-4V/ COMMERCIALLY PURE Ti LAMINATE.

LAMINATE DESIGNATION	PRIMARY/ SECONDARY ALLOYS	0.2% YIELD STRENGTH MPa (ksi)	ULTIMATE STRENGTH MPa (ksi)	% ELONGATION
DT2	Ti-6Al-4V/ CPTi	896 (130)	938 (136)	28.5
		896 (130)	938 (136)	29.8
		Avg. 896 (130)	938 (136)	29.1

* The laminate was nominally 16.4 mm (0.65 in.) thick.

** The primary alloy layers were nominally 3.2 mm (0.125 in.) thick, while the secondary alloy layers were nominally 0.13 mm (0.005 in.) thick.

*** The primary alloy was in a recrystallization annealed condition.

TABLE 13. TENSILE PROPERTIES OF DIFFUSION BONDED ULTRAHIGH CARBON STEEL/INTERSTITIAL FREE IRON LAMINATE.

LAMINATE DESIGNATION	PRIMARY/ SECONDARY ALLOYS	0.2% YIELD STRENGTH MPa (ksi)	ULTIMATE STRENGTH MPa (ksi)	% ELONGATION
DUHC 1	UHC Steel/ Iron	436 (63.2)	486 (70.5)	21.3

The laminate was nominally 2.5 mm (0.10 in.) thick having been rolled down subsequent to diffusion bonding.

laminate are given in Table 13. The strength levels are lower than the sheet properties and the ductility is higher. These variations may be accounted for by the annealing effects associated with the diffusion bonding temperature and times.

Tensile Properties of Adhesively Bonded 7475 Al and 7075 Al Laminates. The adhesively bonded laminates AA1 through AA4 were tested in the as-bonded condition. AA1 was fabricated from 7475-T751 Al sheet while AA2, AA3 and AA4 were made with 7075-T751 Al sheet. The adhesive used was FM73M produced by American Cyanamid. The bonding cure for this adhesive consisted of 121°C (250°F) at 0.34 MPa (50 psi) pressure for one hour. The tensile properties of these laminates are presented in Table 14 and are essentially the same as similarly treated alloys when the contribution to the cross sectional area of the adhesive is taken into account.

Tensile Properties of Roll Bonded 7475 Al/1100 Al Laminate. As reported previously,[21] the laminate RA4 was fabricated and heat treated to the -T7651 temper by the Alcoa Technical Center. The tensile properties for this laminate are given in Table 15. All properties shown are representative of alloy 7475 Al heat treated to the -T7651 temper.

3.2.2 Microstructural Characterization of the Diffusion Bonded Laminates

The microstructures of the diffusion bonded laminates were evaluated using optical metallography and electron probe analysis. Photomicrographs illustrating all the diffusion bonded laminates except DA8 are given on the following pages. DA8 was very similar to DA6. The significant features regarding the microstructures of these laminates are now discussed.

Diffusion Bonded Al/Al Laminate Microstructures. In examining the micrographs, Figures 8, 9, and 10 of the diffusion bonded 7475 Al/1100 Al laminates DA4, DA5 and DA6, it can be seen that the bond interfaces are very clean with no discontinuous third phases present. This is a major accomplishment in light of the difficulties encountered initially in the diffusion bonding of the all aluminum systems.[21] The elimination of the third phase considered to be an oxide was attributable to the enhanced cleaning and handling procedures before and during diffusion bonding. As will be discussed in Section 3.4, these clean bond planes resulted in very good bond plane shear strengths. Also, no problems with delamination during the rather severe quenching procedures necessary in the

TABLE 14. TENSILE PROPERTIES OF ADHESIVELY BONDED 7475 Al AND 7075 Al LAMINATES.

LAMINATE DESIGNATION	PRIMARY ALLOY AND TEMPER	PRIMARY NUMBER OF LAYERS	PRIMARY LAYER THICKNESS mm (in.)	0.2% YIELD STRENGTH MPa (ksi)	ULTIMATE STRENGTH MPa (ksi)	% ELONGATION
AA1	7475-T761 Al	5	2.3 (0.090)	443 (64.2) 441 (63.9) Avg. 442 (64.1)	490 (71.1) 486 (70.4) 488 (70.8)	14.3 14.1 14.2
AA2	7075-T6 Al	9	1.3 (0.050)	468 (67.8) 471 (68.3) Avg. 470 (68.1)	516 (74.8) 518 (75.1) 517 (75.0)	14.7 13.0 13.9
AA3	7075-T6 Al	3	2.3 (0.090)	519 (75.2) 526 (76.2) Avg. 522 (75.7)	559 (81.0) 568 (82.3) 563 (81.7)	15.2 13.9 14.6
AA4	7075-T6 Al	5	2.3 (0.090)	520 (75.4) 526 (76.2) Avg. 523 (75.8)	564 (81.8) 566 (82.1) 565 (82.0)	14.7 14.7 14.7

* The adhesive used was American Cyanamid's FM73M.

** The nominal as-bonded thickness of the adhesive was 0.13 mm (0.005 in.).

FIGURE 15. TENSILE PROPERTIES OF ROLL BONDED 7475 Al/1100 Al LAMINATE.

LAMINATE DESIGNATION	PRIMARY/ SECONDARY ALLOY	0.2% YIELD STRENGTH MPa (ksi)	ULTIMATE STRENGTH MPa (ksi)	% ELONGATION
RA4	7475 Al/ 1100 Al	454 (65.9)	512 (74.2)	16.0
		465 (67.4)	526 (76.3)	15.4
		462 (67.0)	524 (76.0)	14.9
		Avg. 460 (66.8)	521 (75.5)	15.4

* The laminate was heat treated to the -T7651 condition in the primary metal.

** The laminate was nominally 11.9 mm (0.47 in.) thick.

*** Primary alloy layers were nominally 2.3 mm (0.090 in.) thick while secondary alloy layers were normally 0.13 mm (0.005 in.) thick.

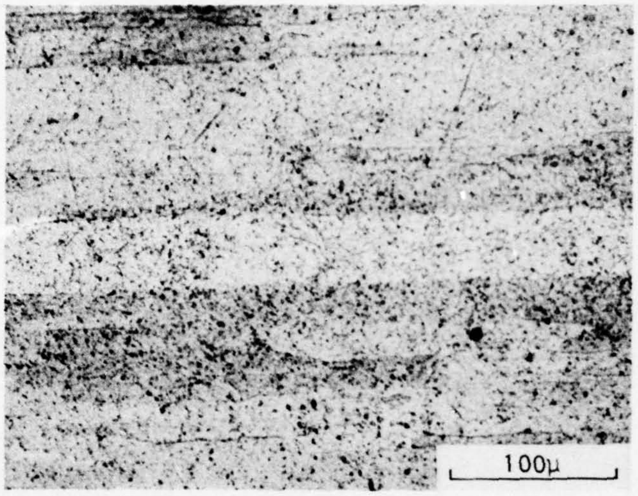


FIGURE 8. MICROGRAPH OF DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DA4 SHOWING 1100 Al INTERLEAF.

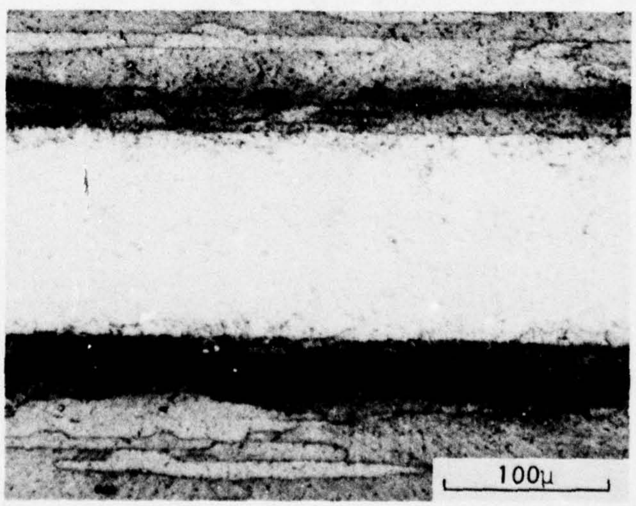


FIGURE 9. MICROGRAPH OF DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DA5 SHOWING 1100 Al INTERLEAF.

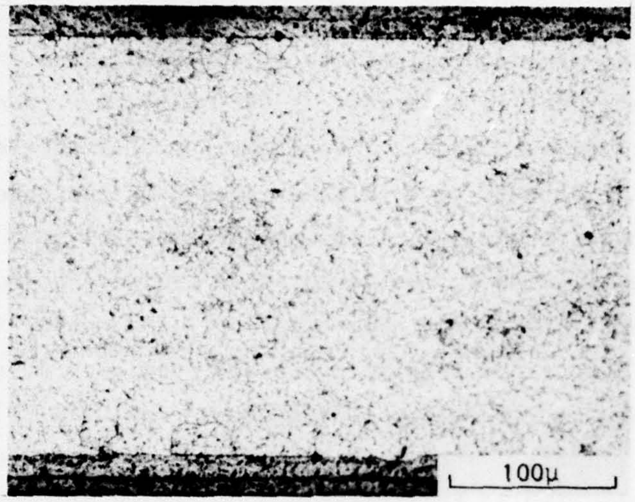


FIGURE 10. MICROGRAPH OF DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DA6 SHOWING 1100 Al INTERLEAF.

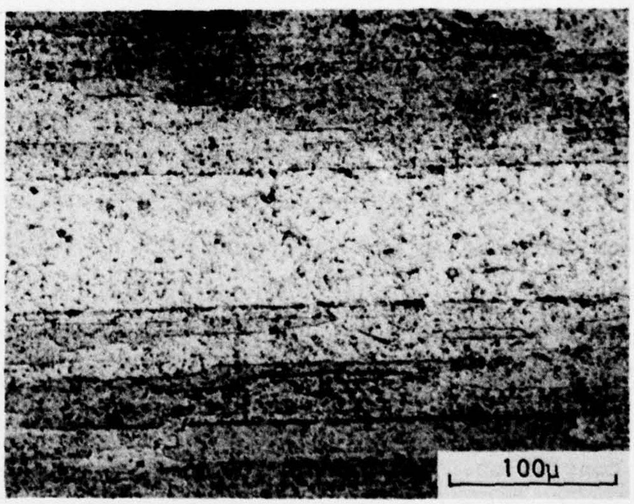
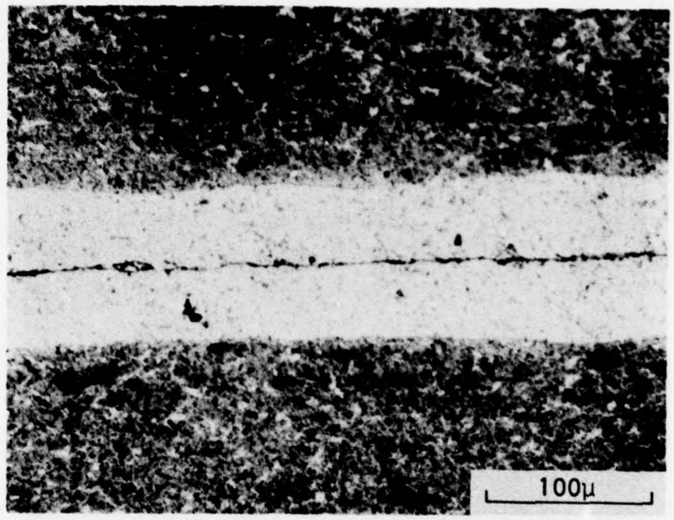


FIGURE 11. MICROGRAPH OF DIFFUSION BONDED 7475 Al/6061 Al LAMINATE DA7 SHOWING 6061 Al INTERLEAF.

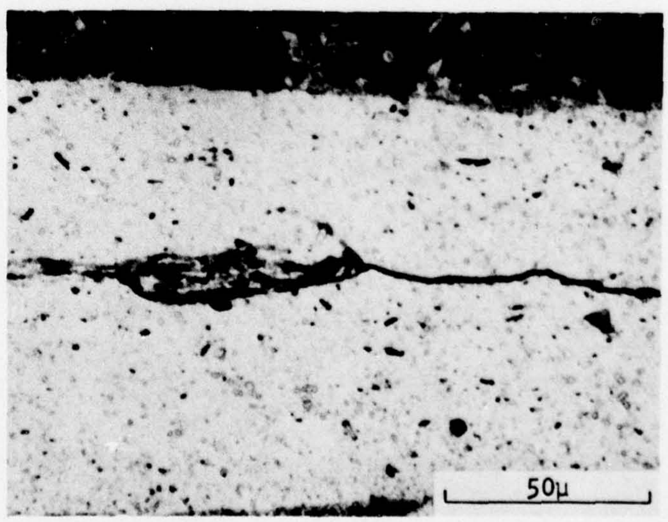
heat treatments of the aluminum alloys were encountered in these laminates. In laminate DA7, Figure 11, some contamination in the bond plane interface region is observable. The interleaf in this case is 6061 Al rather than the 1100 Al used in the laminates discussed above. There were no difficulties with this laminate which were attributable to this minor amount of the observed discontinuous third phase formation. This was, unfortunately, not the case with DA9, Figure 12. As was previously mentioned, this laminate delaminated completely upon sample machining and/or heat treating. The reason is obvious from the photomicrograph. A continuous third phase and even gaps in some cases may be observed to be present at the plane of contact between the 7072 Al Alclad layers on the 7075 Al primary. The cleaning and/or bonding procedures were inadequate to achieve bonding in this totally 7000 series aluminum laminate. This is indeed unfortunate because from a processing standpoint, it is very attractive to eliminate the separate secondary layers in the form of foils from the bonding procedures. Perhaps with a different cladding material and the use of alternate clad and unclad primary sheets, this problem could be overcome.

<u>Diffusion Bonded Ti-6Al-4V/CPTi Laminate</u>. The microstructure of the diffusion bonded Ti-6Al-4V/CPTi laminate, Figure 13, reveals a fine recrystallized grain size in the primary and some dark etching constituent in the interleaf CPTi using Kroll's reagent. These dark particles were unidentified but may be relatively high in vanadium as deduced from an electron beam microprobe scan for elemental analysis which is discussed presently. There was very little bond plane contamination and bonding was very good with no delaminations at the bond plane observed under the testing conditions employed. It was thought, initially, that perhaps either or both the bonding temperature and time used, i.e., 871°C (1600°F) for one hour, were excessive because these laminates were incapable of crack arrest. The diffusion profile of Al discussed presently does not substantiate this conclusion. This point will need clarification before an all-titanium laminate can be used in a damage tolerant structure.

<u>Ultrahigh Carbon Steel/Iron Laminate Microstructures</u>. The microstructure of the UHC Steel/Iron laminate, Figure 14, shows the very fine grain size of the superplastically formable UHC steel. Continuous grains across the bond plane interfaces may also be seen. No contamination is noted and bonding is very good.



(a)



(b)

FIGURE 12. MICROGRAPHS OF DIFFUSION BONDED 7075 Al/7072 Al LAMINATE DA9 SHOWING: (a) 7072 Al INTERLEAF; (b) 7075 Al/7072 Al INTERFACE.

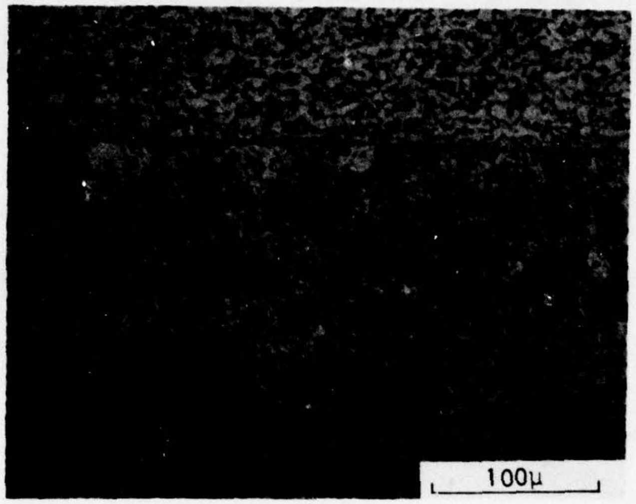
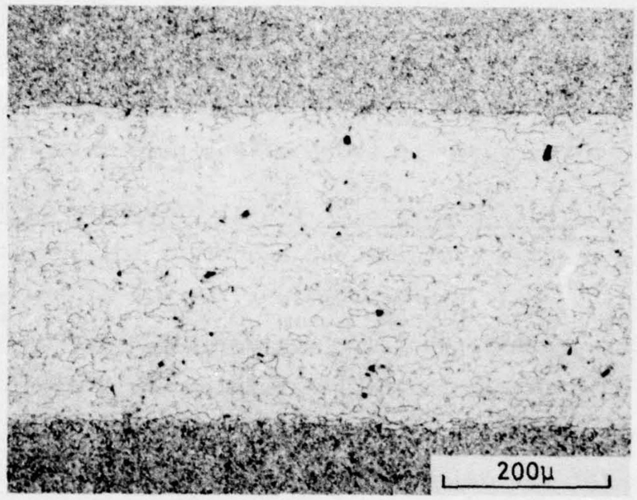
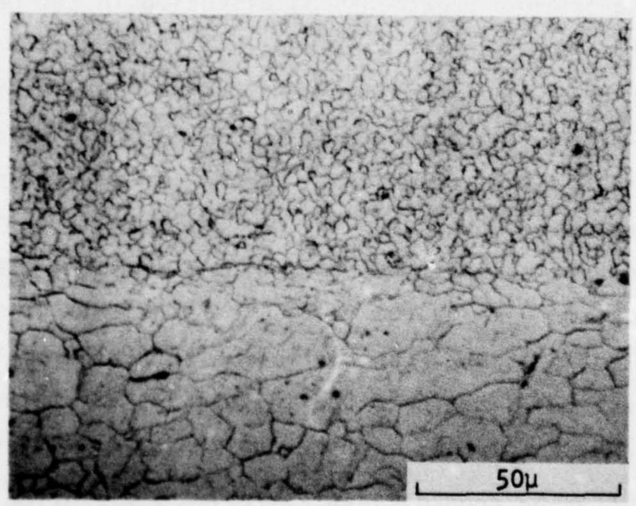


FIGURE 13. MICROGRAPH OF DIFFUSION BONDED Ti-6Al-4V/CPTi LAMINATE DT2 SHOWING CP Ti INTERLEAF.



(a)



(b)

FIGURE 14. MICROGRAPHS OF DIFFUSION BONDED UHC STEEL/IRON LAMINATE DUHC 1 SHOWING: (a) IRON INTERLEAF; (b) UHC STEEL/IRON INTERFACE.

Roll and Adhesively Bonded Al/Al Laminates. The roll bonded material was discussed previously[21] and that discussion will not be repeated here. The adhesively bonded samples exhibited nothing noteworthy, having essentially identical microstructures to those of the base materials.

Electron Probe Microanalysis of Diffusion Bonded Laminates. Electron probe microanalysis was used to evaluate the amount of solid state atomic diffusion across the secondary metal interleaf alloys for six of the eight diffusion bonded laminates studied in this program. Laminates DA6 and DA9 were not evaluated because of the redundancies in interleaf thickness and primary alloy between DA6 and DA4 in the first case and the poor bonding in DA9 in the second. The diffusion profiles for the major alloying elements in the all aluminum laminates, i.e., Zn, Mg and Cu, are shown in Figures 15 through 18. It can be seen that the interleaf thickness significantly affects the diffusion profiles. For example comparisons of Figures 15, 16 and 17 show that the thinner the interleaf, the lower the gradients for the primary alloying elements in the secondary interleaf metal. It is evident that in laminate DA4, Figure 15, (0.05 mm interleaf thickness) sufficient diffusion had occurred to make the interleaf hardenable by precipitation hardening thermal treatments as discussed in the next section. Such a strengthening of the interleaf can lead to failure of the laminate in a manner similar to that of a monolithic material. As will be seen later, failure in this laminate did indeed simulate that of a monolithic material but not with the anticipated loss in fracture toughness. This laminate retained its crack arrest capability under static overloads but not under fatigue cyclic stressing. Therefore, this interleaf thickness for the bonding conditions employed in this study is considered just marginally too thin. The gradients in the other Al/Al laminates were sufficiently steep, i.e., diffusion sufficiently limited to retain the weak interleaf character. Laminate DA8, Figure 18, exhibited a very similar gradient to laminate DA5, Figure 16, both having the same interleaf thicknesses.

For the diffusion bonded Ti-6Al-4V/CPTi, a diffusion profile for Al is given in Figure 19. A vanadium standard was not currently available and it was not profiled. Qualitatively, however, it was observed that there was a significant quantity of vanadium in the as-bonded commercially pure Ti interleaf. The reason for this is not known at this time. The aluminum profile shows a very steep gradient at the original bond plane interfaces indicating that diffusion was rather limited as desired. As will be discussed later, this

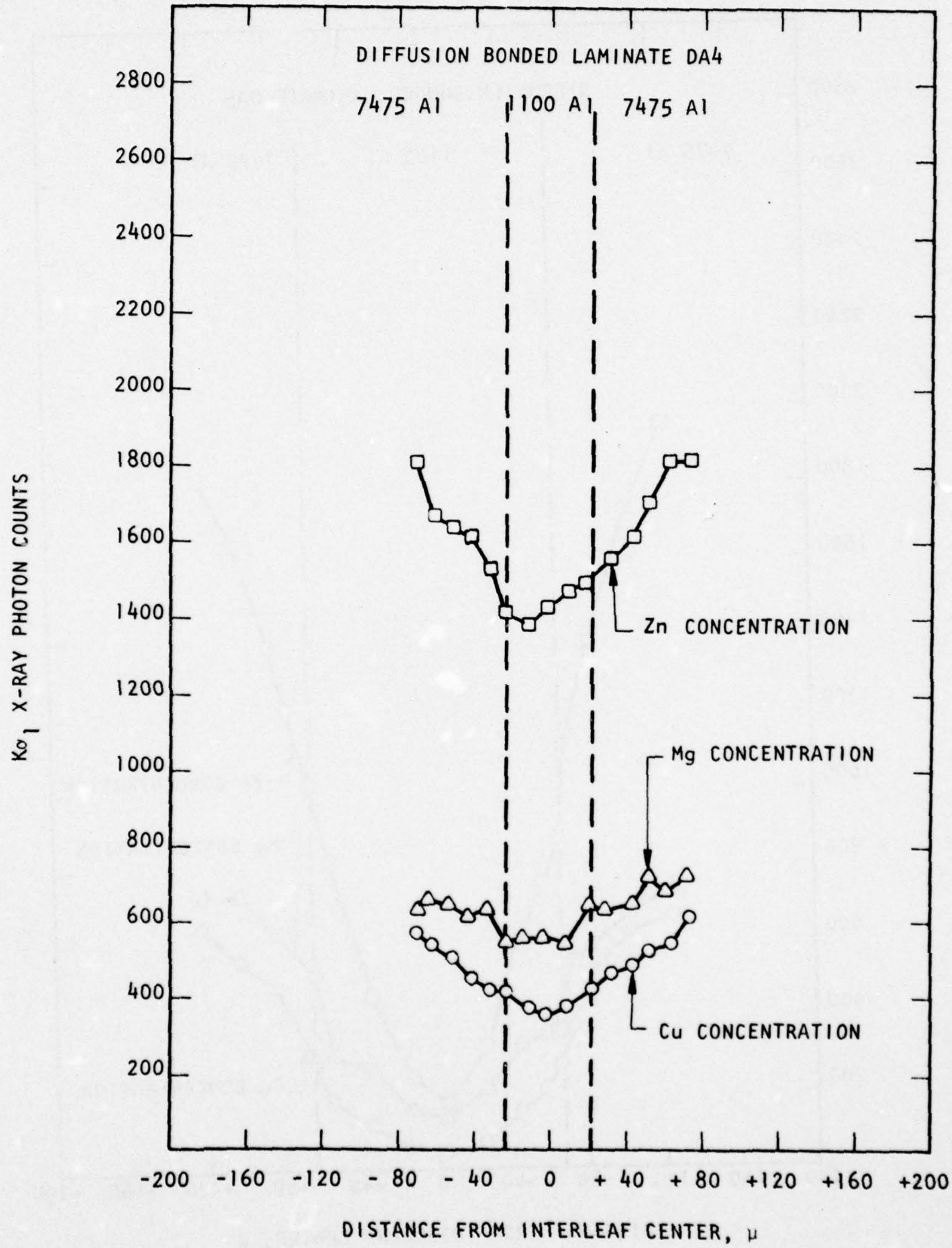


FIGURE 15. Zn, Mg, and Cu DIFFUSION PROFILES ACROSS 0.05 mm (0.002 in.) 1100 Al INTERLEAF IN DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DA4 (HEAT TREATED TO -T651 TEMPER).

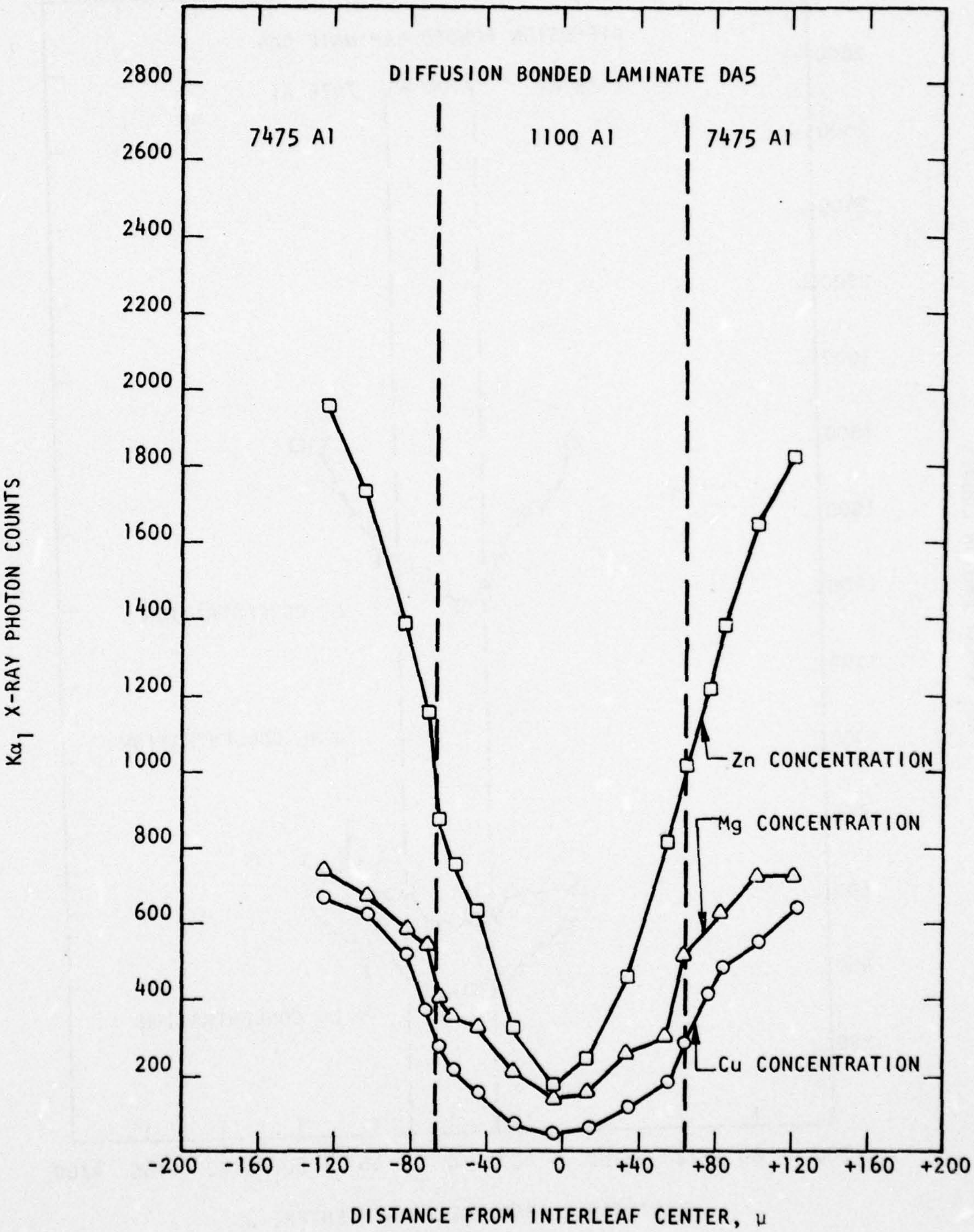


FIGURE 16. Zn, Mg, and Cu DIFFUSION PROFILES ACROSS 0.10 mm (0.004 In.) 1100 Al INTERLEAF IN DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DA5 (HEAT TREATED TO -T651 TEMPER).

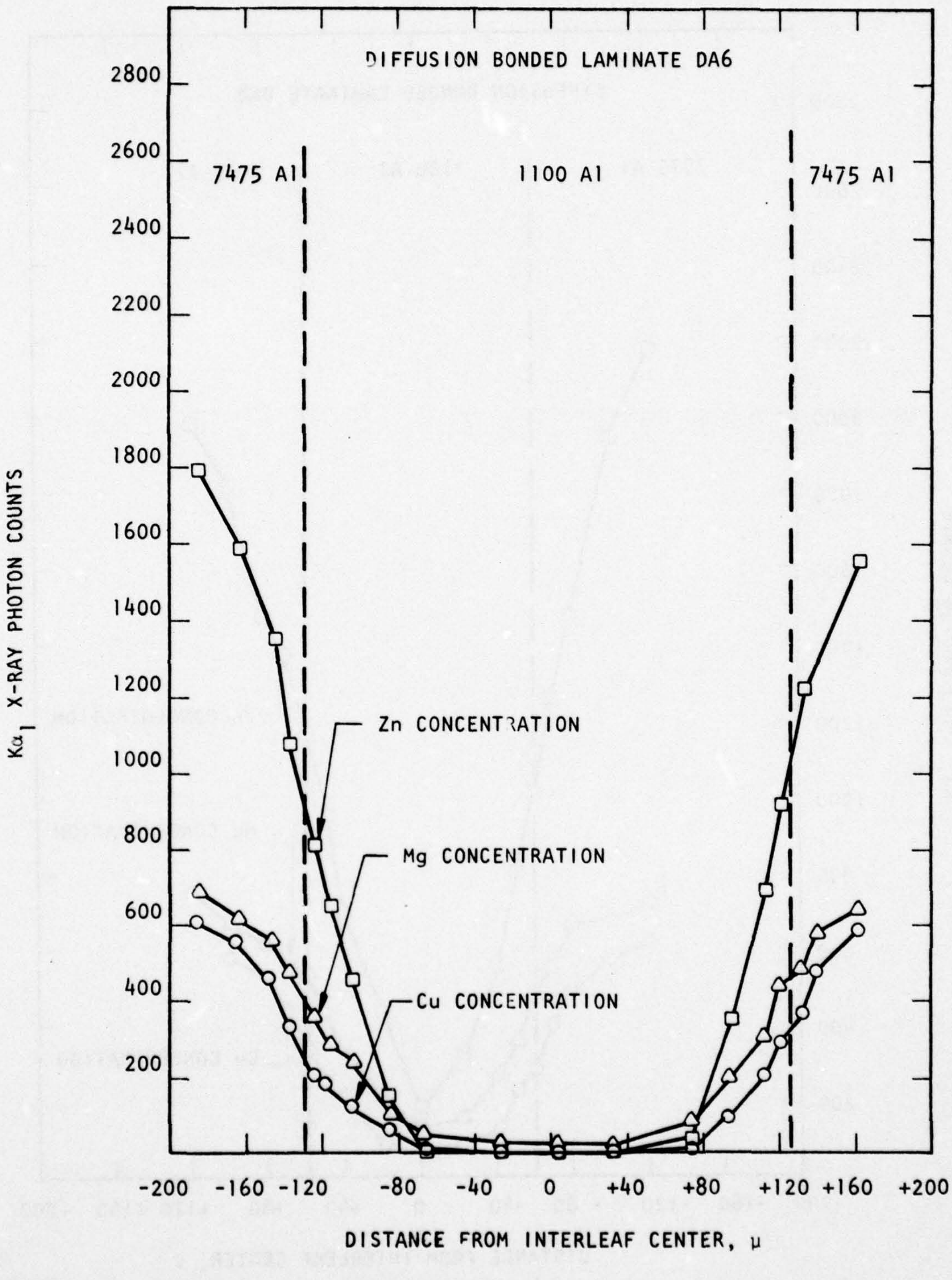


FIGURE 17. Zn, Mg, and Cu DIFFUSION PROFILES ACROSS 0.25 mm (0.010 in.) 1100 Al INTERLEAF IN DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DA6 (HEAT TREATED TO -T651 TEMPER).

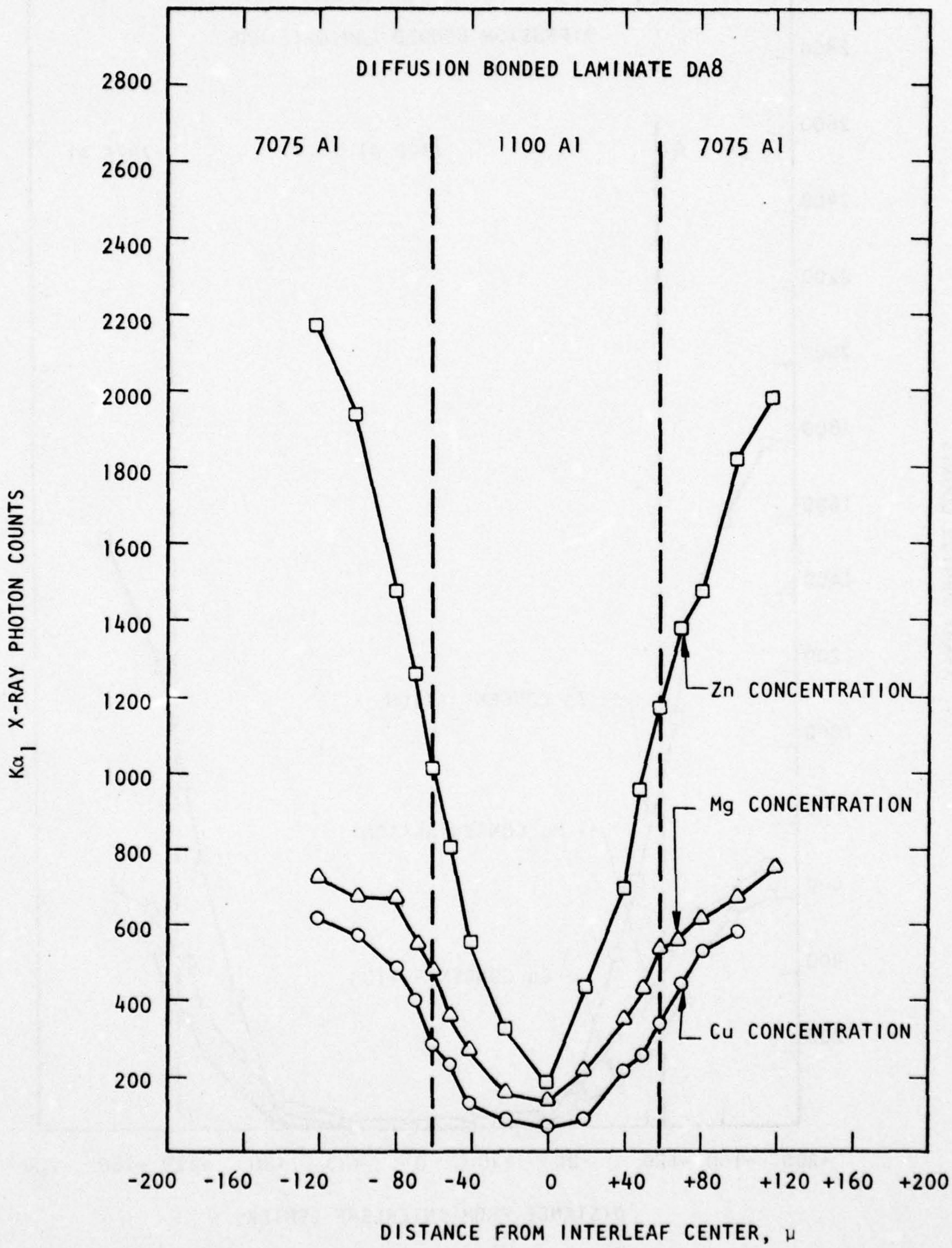


FIGURE 18. Zn, Mg, and Cu DIFFUSION PROFILES ACROSS 0.10 mm (0.004 in.) 1100 Al INTERLEAF IN DIFFUSION BONDED 7075 Al/1100 Al LAMINATE DA8 (HEAT TREATED TO -T651 TEMPER).

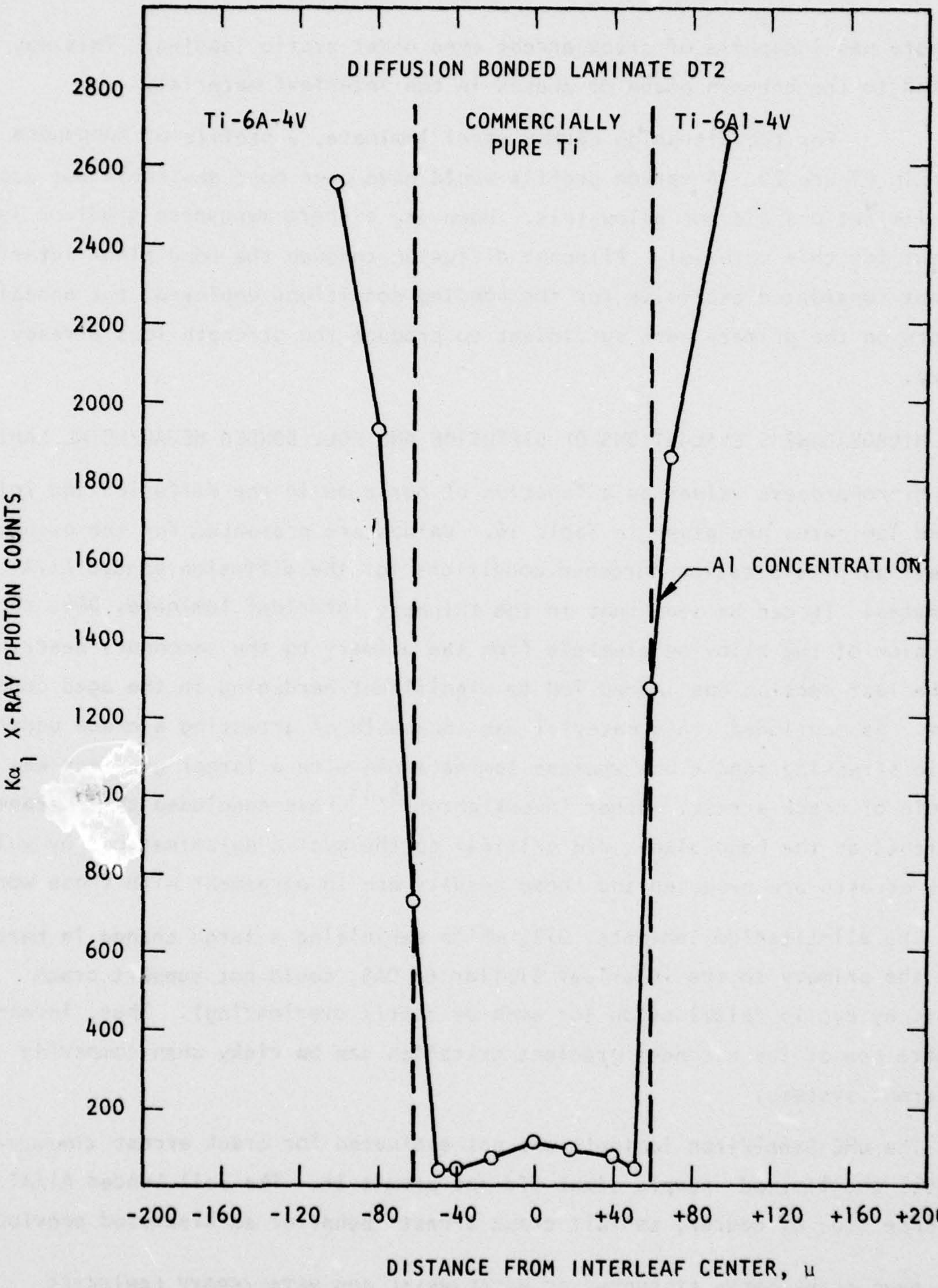


FIGURE 19. Al DIFFUSION PROFILE ACROSS 0.13 mm (0.005 in.) COMMERCIALLY PURE Ti INTERLEAF IN DIFFUSION BONDED Ti-6Al-4V/CPTi LAMINATE DT2.

laminate was incapable of crack arrest even under static loading. This may be related to the unknown phase or phases in the interleaf material.

For the ultrahigh carbon steel laminate, a profile of manganese is given in Figure 20. A carbon profile would have been most desirable but equipment limitations did not allow this. However, a sharp manganese gradient is evident for this material. Although diffusion through the bond plane interfaces was not considered excessive for the bonding conditions employed, the annealing effects on the primary were sufficient to produce the strength loss already described.

3.3 MICROHARDNESS EVALUATIONS OF DIFFUSION AND ROLL BONDED METAL/METAL LAMINATES

Microhardness values as a function of position in the diffusion and roll bonded laminates are given in Table 16. Values are presented for the as-bonded as well as precipitation hardened conditions for the diffusion bonded Al/Al laminates. It can be seen that in the thinnest interleaf laminate, DA4, the diffusion of the alloying elements from the primary to the secondary described in the last section has indeed led to significant hardening in the aged conditions. As mentioned, this material was incapable of arresting a crack under cyclic stressing conditions whereas laminate DA5 with a larger gradient was capable of crack arrest. Other investigators[4,34] have concluded that hardness gradients at the bond planes are critical to the cyclic delaminations by which crack arrests are produced and these results are in agreement with those workers.

The all-titanium laminate, DT2, while exhibiting a large change in hardness from the primary to the interleaf similar to DA5, could not support crack arrest by cyclic delamination (or even by static overloading). Thus, indescrimate use of the hardness gradient criterion can be risky when comparing different systems.

The UHC Steel/Iron laminate was not evaluated for crack arrest characteristics because the limited sample sizes did not permit it. The roll bonded Al/Al laminate did, of course, exhibit crack arrest behavior as discussed previously.[21]

3.4 BOND PLANE SHEAR STRENGTHS OF METAL/METAL AND METAL/EPOXY LAMINATES

The bond plane compressive shear strengths were determined in the laminates using the compact compressive lap shear specimen shown in Figure 3. The values

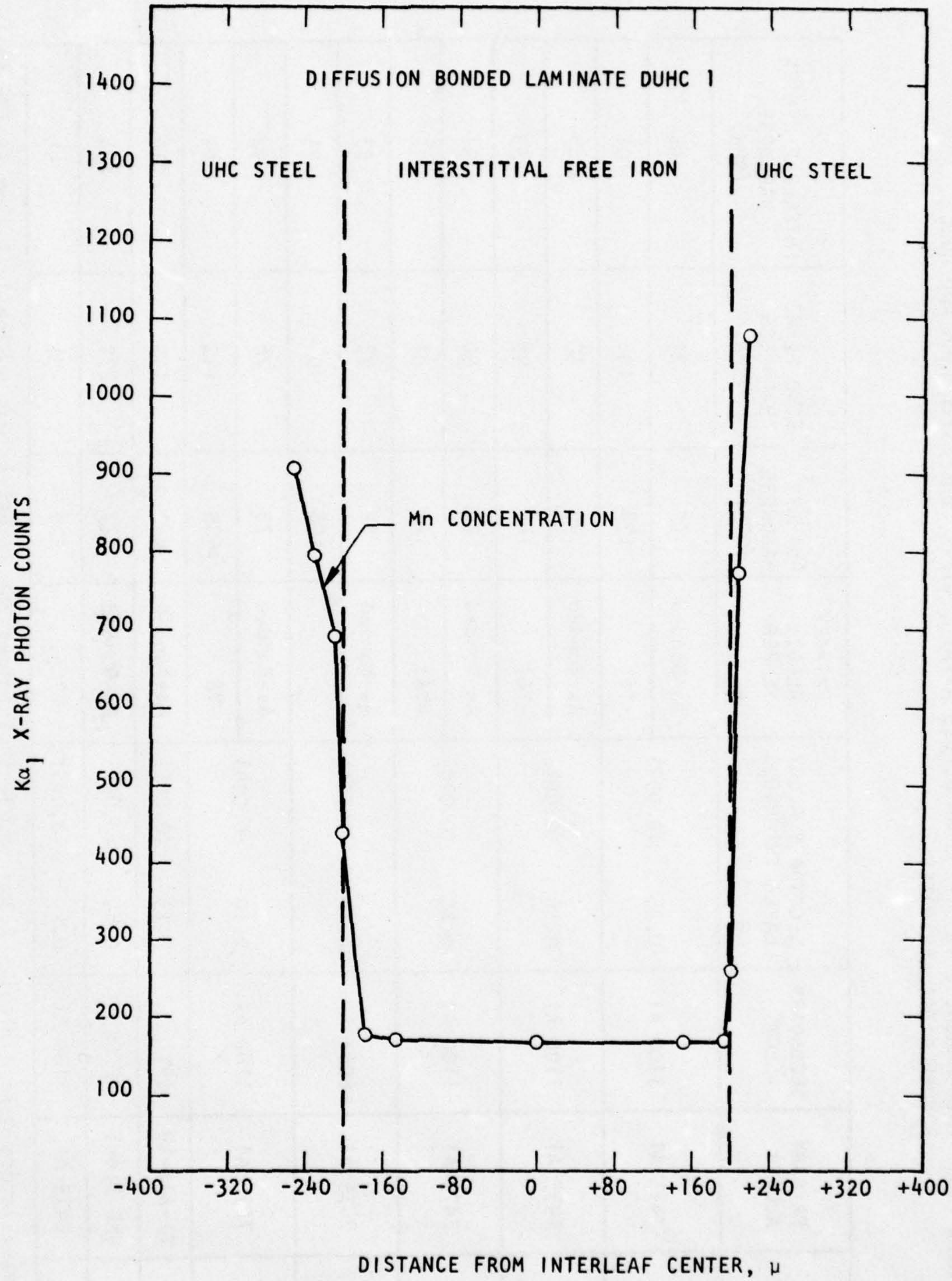


FIGURE 20. Mn DIFFUSION PROFILE ACROSS 0.40 mm (0.016 in.) INTERSTITIAL FREE IRON INTERLEAF IN DIFFUSION BONDED ULTRAHIGH CARBON STEEL/ IRON LAMINATE DUHC 1.

TABLE 16. MICROHARDNESS IN DIFFUSION BONDED Al/Al, Ti/Ti, UHC STEEL/IRON AND ROLL BONDED Al/Al LAMINATES

DESIGNATION	PRIMARY ALLOY*	SECONDARY ALLOY*	SECONDARY ALLOY LAYER THICKNESS mm (in.)	PRIMARY ALLOY TEMPER	PRIMARY HARDNESS (DPN)**	BOND PLANE HARDNESS (DPN)	INTERLEAF CENTER HARDNESS (DPN)
DA4	7475 Al	1100 Al	0.05 (0.002)	As-Bonded	65	73	58
				-T61	178	106	101
DA5	7475 Al	1100 Al	0.10 (0.004)	As-Bonded	70	68	47
				-T61	168	93	59
DA6	7475 Al	1100 Al	0.25 (0.010)	As-Bonded	70	50	31
				-T61	168	101	38
DA7	7475 Al	6061 Al	0.10 (0.004)	As-Bonded	82	73	57
					158	101	93
DA8	7075 Al	1100 Al	0.10 (0.004)	As-Bonded	79	76	42
				-T6	189	112	44
DT2	Ti-6Al-4V	CPTi	0.13 (0.005)	As-Bonded	460	255	210
DUCH 1	UHC Steel	IF Fe	0.80 (0.03)	As-Bonded	337	272	154
RA4	7475 Al	1100 Al	0.1 (0.005)	-T7651	225	51	45

*The Al primary layers were nominally 2.3mm (0.090 in.) thick; the Ti-6Al-4V was nominally 3.2 mm (0.125 in.). thick; the UHC steel was nominally 1.6 mm (0.063 in.) thick.

**Diamond Pyramid Hardness Number.

recorded for the diffusion bonded Al/Al and Ti/Ti and adhesively bonded Al/Epoxy laminates are given in Tables 17, 18 and 19 respectively. In Table 17, both the as-bonded and heat treated strengths are presented for the all aluminum laminates. In a number of cases, the as-bonded samples being very soft from the heat cycle involved with bonding, were unable to sustain the compressive load applied. These samples bent before a shearing of the bond plane was obtained. This is of course indicative of the good bonding which is necessary for the resistance to delamination from the thermally induced stresses encountered in the subsequent quenching procedures of the precipitation hardening treatments. In both the as-bonded and heat treated conditions, a progressive increase in strength is observed as the interleaf thickness is decreased as would be expected. For example, the heat treated laminate DA4 with the 0.05 mm (0.002 in.) interleaf had an ultimate bond plane compressive shear strength of 213 MPa (30.8 ksi) compared to 103 MPa (14.9 ksi) for DA6 with 0.25 mm (0.010) interleaf. In Table 18 results for the diffusion bonded Ti-6Al-4V/CPTi laminate DT2 are given. This laminate was only evaluated in the as-bonded condition and it can be seen that very high shear strengths were recorded for this material. These strengths approach the values for the CPTi itself and indicate no tendencies for delaminations of this laminate.

Values of shear strengths for the adhesively bonded laminates AA1 and AA4 which are given in Table 19 show that bonding was good for both alloys, 7475 Al and 7075 Al, and that the surface preparations utilized were appropriate. The values of 33 MPa (4.8 ksi) for the yield strength in shear and 38 MPa (5.5 ksi) for the ultimate shear strength are equal to the values given by the manufacturer of this epoxy.[35]

TABLE 17. BOND PLANE COMPRESSIVE SHEAR STRENGTHS OF DIFFUSION BONDED Al/Al LAMINATES

LAMINATE DESIGNATION	PRIMARY/ SECONDARY	SECONDARY THICKNESS mm (in.)	AS BONDED 0.2% YIELD STRENGTH MPa (ksi)	AS BONDED ULTIMATE STRENGTH MPa (ksi)	HEAT TREATED PRIMARY ALLOY TEMPER	HEAT TREATED 0.2% YIELD STRENGTH MPa (ksi)	HEAT TREATED ULTIMATE STRENGTH MPa (ksi)
DA4	7475 Al/1100 Al	0.05 (0.002)	71.7 (10.4) 66.2 (9.6) 69.0 (10.0) Avg 69.0 (10.0)	134 (19.4) 138 (20.0) 138 (20.0) 137 (19.8)	-T61	138 (20.0) 152 (22.0) 139 (20.1) 143 (20.7)	212 (30.8) 214 (31.1) 211 (30.6) 213 (30.8)
DA5	7475 Al/1100 Al	0.10 (0.004)	>60.0 >(8.7) >52.5 >(8.3) >57.2 >(8.3) Avg>58.1 >(8.4)	>106>(15.4) >110>(15.9) >104>(15.1) >107>(15.5)	-T61	>53.1 >(7.7) 105 (15.2) 101 (14.7) >86.4>(12.5)	>106>(15.3) 138 (20.0) 124 (18.0) >123>(17.8)
					-T76	108 (15.6) 118 (17.1) 123 (17.9) 116 (16.9)	151 (21.9) 150 (21.8) 152 (221.) 151 (21.9)
DA6	7475 Al/1100 Al	0.25 (0.010)	42.7 (6.2) 43.4 (6.3) 45.5 (6.6) Avg 44.1 (6.4)	72.4 (10.5) >110>(16.0) 91.7 (13.3) >104>(13.3)	-T61	55.8 (8.1) 51.0 (7.4) 55.8 (8.1) 54.2 (7.9)	101 (14.6) 104 (15.1) 103 (15.0) 103 (14.9)
DA7	7475 Al/6061 Al	0.10 (0.004)	59.3 (8.6) 62.1 (9.0) 60.0 (8.7) Avg 60.4 (8.8)	59.3 (8.6) >138 >(20) >138 >(20) >112 >(16)	-T61	138 (20.0) 146 (21.1) 143 (20.8) 142 (20.6)	217 (31.4) 198 (28.7) 203 (29.5) 206 (29.9)
DA8	7075 Al/1100 Al	0.10 (0.004)	>69.0>(10.0) 66.9 (9.7) 54.5 (7.9) Avg>63.4 >(9.2)	>130>(18.9) 139 (20.1) 126 (18.3) >132>(19.1)	-T61	116 (16.8) 106 (15.3) 110 (16.0) 111 (16.0)	161 (23.3) 143 (20.7) 155 (22.5) 153 (22.2)

*The symbol > (greater than) indicates the specimen bent before shearing in the bond plane.

TABLE 18. BOND PLANE COMPRESSIVE SHEAR STRENGTHS OF DIFFUSION BONDED Ti-6Al-4V/CPTi LAMINATE

LAMINATE DESIGNATION	PRIMARY/ SECONDARY	SECONDARY THICKNESS mm (in.)		AS-BONDED 0.2% YIELD STRENGTH MPa	(ksi)	ULTIMATE STRENGTH MPa	(ksi)
DT2	Ti-6Al-4V/CPTi	0.13(0.005)		287	(41.6)	455	(66.0)
				296	(42.9)	456	(66.2)
				303	(44.0)	452	(65.2
			Avg	295	(42.8)	454	(65.9)

TABLE 19. BOND PLANE COMPRESSIVE SHEAR STRENGTHS OF ADHESIVELY BONDED Al/EPOXY LAMINATES

LAMINATE DESIGNATION	SECONDARY	SECONDARY THICKNESS mm (in.)	HEAT TREATED PRIOR TO BONDING PRIMARY ALLOY TEMPER		0.2% YIELD STRENGTH MPa	(ksi)	ULTIMATE STRENGTH MPa	(ksi)
AA1	7475 Al/ FM73M	0.13 (0.005)	-T6		32	(4.7)	37	(5.3)
					34	(5.0)	39	(5.6)
					33	(4.8)	37	(5.4)
				Avg	33	(4.8)	38	(5.4)
AA4	7075 Al/ FM73M	0.13 (0.005)	-T6		35	(5.1)	39	(5.7)
					36	(5.2)	38	(5.5)
					34	(4.9)	37	(5.4)
				Avg	35	(4.8)	38	(5.5)

3.5 FRACTURE PROPERTIES OF LAMINATES

3.5.1 Fracture of Crack Divider Metal/Metal and Metal/Epoxy Laminates

Diffusion and Adhesively Bonded 7475 Al and 7075 Al Laminates Fracture Results. The fracture toughness values of the diffusion bonded Al/Al laminates DA4, DA5, DA6, DA7 and DA8 are given in Table 20. The values for the adhesively bonded laminates AA1, AA2, AA3 and AA4 are given in Table 21. These fracture results were determined on laminate materials heat treated as indicated. All tests were conducted with compact tension specimens (Figure 4).

The results illustrated in Tables 20 and 21 show that these diffusion and adhesively bonded laminates had remarkably improved critical fracture toughness (K_c) values above the corresponding monolithic 7475 Al and 7075 Al of similar heat treatments listed earlier in Table 9 of Section 3.1. (Critical fracture toughness is considered the most representative measure of toughness improvement in these laminate materials, since they do not approach plane strain fracture behavior. This same conclusion has been reached by previous investigators,[3,6] who used K_c as the most representative measure of toughness in crack divider laminates).

Table 22 shows comparative average K_c values for single layer 7475-T61 and -T761 aluminum sheet, 7475-T651 and -T7651 monolithic aluminum plate and diffusion and adhesively bonded 7475 Al laminates similarly heat treated. The values recorded for the -T61 and -T651 conditions in the monolithic sheet and plate were obtained from the literature[31] and comparisons made to those values should be considered to be only semi-quantitative. However, it can be seen that improvements in toughness are definitely obtained through the lamination procedures used when these laminates are compared to monolithic plates of similar thickness and heat treatment condition. Table 23 shows comparative average K_c values for 7075-T6 aluminum sheet, 7075-T651 monolithic aluminum plate and diffusion and adhesively bonded 7075 Al laminates. Critical fracture toughnesses for these laminates are again markedly improved over monolithic values. The following observations can be made from the comparisons in Tables 22 and 23:

(1) The diffusion and adhesively bonded 7475-T651 and -T7651 laminates had essentially the same fracture toughness, regardless of secondary material or interleaf thickness.

TABLE 20. CRACK DIVIDER, L-T ORIENTATION FRACTURE TOUGHNESS VALUES OF DIFFUSION BONDED 7475 Al/1100 Al, 7475 Al/6061 Al, and 7075 Al/1100 Al LAMINATES

LAMINATE DESIGNATION	PRIMARY ALLOY AND TEMPER	SECONDARY ALLOY	SECONDARY ALLOY LAYER THICKNESS mm	(in.)		CONDITIONAL FRACTURE TOUGHNESS, K_Q MPa $\sqrt{m}$	(ksi $\sqrt{in.}$)	APPARENT FRACTURE TOUGHNESS, K_{app} MPa $\sqrt{m}$	(ksi $\sqrt{in.}$)	CRITICAL FRACTURE TOUGHNESS, K_c MPa $\sqrt{m}$	(ksi $\sqrt{in.}$)
DA4	7475-T651 Al	1100 Al	0.05	(0.002)		53.3	(48.5)	66.0	(60.1)	96.9	(88.3)
						52.0	(47.3)	66.5	(60.5)	93.5	(85.1)
						53.5	(48.7)	66.3	(60.3)	85.6	(77.9)
					Avg.	52.9	(48.2)	66.3	(60.3)	92.0	(83.7)
DA5	7475-T651 Al	1100 Al	0.10	(0.004)		50.2	(45.7)	68.6	(62.4	92.5	(84.2)
						46.9	(42.7)	65.1	(59.2)	89.5	(81.4)
						49.9	(45.4)	67.9	(61.8)	95.0	(86.4)
					Avg.	49.0	(44.6)	67.2	(61.1)	92.3	(84.0)
	7475-T7651 Al	1100 Al	0.10	(0.004)		35.3	(32.1)	61.2	(55.7)	111	(101)
						47.7	(43.4)	68.0	(61.9)	96.4	(87.7)
						33.2	(30.2)	61.9	(56.3)	104	(94.5)
					Avg.	38.7	(35.2)	63.7	(58.0)	104	(94.4)
DA6	7475-T651 Al	1100 Al	0.25	(0.010)		42.1	(38.3)	73.1	(66.5)	95.8	(87.2)
						39.5	(35.9)	71.5	(65.1)	95.2	(86.6)
						40.9	(37.2)	69.6	(63.3)	92.8	(84.4)
					Avg.	40.8	(37.1)	71.4	(65.0)	94.8	(86.1)
DA7	7475-T651 Al	6061 Al	0.10	(0.004)		46.6	(42.4)	74.2	(67.5)	96.2	(87.5)
						51.4	(46.8)	74.7	(68.0)	95.2	(86.6)
						48.5	(50.0)	76.6	(69.7)	98.0	(89.2)
					Avg.	47.8	(43.5)	75.2	(68.4)	96.5	(87.8)
DA8	7075-T641 Al	1100 Al	0.10	(0.004)		30.1	(27.4)	37.7	(34.3)	50.9	(46.3)
						30.3	(27.6)	39.0	(35.5)	55.0	(50.0)
						30.3	(27.6)	36.6	(33.3)	51.7	(47.0)
					Avg.	30.3	(27.5)	37.8	(34.4)	52.5	(47.8)

* Laminates were nominally 11.9 mm (0.47 in.) thick.
** Primary alloy (7475 Al or 7075 Al) layers were nominally 2.3 mm (0.090 in.) thick.
*** Specimen type used was compact tension.

TABLE 21. CRACK DIVIDER, L-T ORIENTATION FRACTURE TOUGHNESS VALUES OF ADHESIVELY BONDED 7475 Al/EPOXY AND 7075 Al/EPOXY LAMINATES

LAMINATE DESIGNATION	PRIMARY ALLOY AND TEMPER	PRIMARY THICKNESS mm	(in.)	NUMBER OF PRIMARY LAYERS	SECONDARY MATERIAL		CONDITIONAL FRACTURE TOUGHNESS, K_Q MPa $\sqrt{m}$	(ksi $\sqrt{in.}$)	APPARENT FRACTURE TOUGHNESS, K_{app} MPa $\sqrt{m}$	(ksi $\sqrt{in.}$)	CRITICAL FRACTURE TOUGHNESS, K_c MPa $\sqrt{m}$	(ksi $\sqrt{in.}$)
AA1	7475-T761	2.3	(0.090)	5	FM73M		47.5	(43.2)	74.8	(68.1)	92.8	(84.5)
							48.3	(44.0)	74.4	(67.7)	94.2	(85.7)
							44.7	(40.7)	71.4	(65.3)	93.4	(85.0)
						Avg.	46.8	(42.6)	73.5	(67.0)	93.4	(85.1)
AA2	7075-T6	1.3	(0.050)	9	FM73M		46.0	(41.9)	58.1	(52.9)	66.3	(60.3)
							46.8	(42.6)	58.2	(53.0)	64.4	(58.6)
							43.2	(39.3)	59.0	(53.7)	67.6	(61.5)
						Avg.	45.3	(41.3)	58.4	(53.2)	66.1	(60.1)
AA3	7075-T6	2.3	(0.090)	3	FM73M		35.1	(31.9)	48.1	(43.8)	55.4	(50.4)
							31.9	(29.0)	48.1	(43.8)	55.5	(50.5)
							33.2	(30.2)	46.0	(41.9)	56.0	(5.10)
						Avg.	33.4	(30.4)	47.4	(43.2)	55.6	(50.6)
AA4	7075-T6	2.3	(0.090)	5	FM73M		31.5	(28.7)	47.8	(43.5)	53.3	(48.5)
							32.0	(29.1)	46.5	(42.3)	52.1	(47.4)
							33.7	(30.7	49.1	(44.7)	54.9	(50.0)
						Avg.	32.4	(29.5)	47.8	(43.5)	53.4	(48.6)

* Laminates AA1 and AA4 were nominally 11.9 mm (0.47 in.) thick; AA2 was nominally 12.5 mm (0.49 in.) thick; AA3 was nominally 7.1 mm (0.28 in.) thick.

** Specimen type used was compact tension.

TABLE 22. COMPARISONS OF AVERAGE CRITICAL FRACTURE TOUGHNESS VALUES (CRACK DIVIDER, L-T ORIENTATION) FOR 7475-T61 AND -T761 AL MONOLITHIC SHEET AND PLATE AND DIFFUSION AND ADHESIVELY BONDED 7475 Al SIMILARLY HEAT TREATED

MATERIAL	NOMINAL THICKNESS mm (in.)	SECONDARY MATERIAL	INTERLEAF THICKNESS mm (in.)	CRITICAL FRACTURE TOUGHNESS, K_c MPa$\sqrt{m}$ (ksi $\sqrt{in.}$)	% RETENTION OF SINGLE LAYER SHEET TOUGHNESS	% INCREASE ABOVE MONOLITHIC PLATE TOUGHNESS
Single layer 7475-T61 Al Sheet	Average Sheet* 2.5 (0.100)	---	---	104 (95)	---	---
Monolithic 7475-T651 Al Plate	Average Plate* 12.7 (0.50)	---	---	44 (40)	---	---
Single Layer 7475-T761 Al Sheet	2.3 (0.090)	---	---	90.1 (82.0)	---	---
Monolithic 7475-T7651 Al Plate	11.9 (0.47)	---	---	66.3 (60.3)	---	---
Diffusion Bonded 7475-T651 Al Laminates	11.9 (0.47	1100 Al	0.05 (0.002)	92.0 (83.7)	88%	109%
			0.10 (0.004)	92.3 (84.0)	89%	110%
			0.25 (0.010)	94.8 (86.1)	91%	115%
		6061 Al	0.10 (0.004)	96.5 (87.8)	93%	119%
Diffusion Bonded 7475-T7651 Al Laminate	11.9 (0.47)	1100 Al	0.10 (0.004)	104 (94.4)	115%	57%
Adhesively Bonded 7475-T761 Al Laminate	11.9 (0.47)	FM73M	0.13 (0.005)	93.4 (85.1)	104%	41%

*Average sheet and plate values from reference 31.

**K_c values determined from compact tension samples.

TABLE 23. COMPARISONS OF AVERAGE CRITICAL FRACTURE TOUGHNESS VALUES (CRACK DIVIDER, L-T ORIENTATION) FOR 7075-T6 AND -T651 Al MONOLITHIC SHEET AND PLATE AND DIFFUSION AND ADHESIVELY BONDED 7075-T651 AND -T6 LAMINATES

MATERIAL	NOMINAL PRIMARY THICKNESS mm (in.)	NOMINAL LAMINATE THICKNESS mm (in.)	SECONDARY MATERIAL	INTERLEAF THICKNESS mm (in.)	CRITICAL FRACTURE TOUGHNESS, K_c MPa $\sqrt{m}$ (ksi $\sqrt{in.}$)	% RETENTION OF SINGLE LAYER SHEET TOUGHNESS	% INCREASE ABOVE MONOLITHIC PLATE TOUGHNESS
Single Layer 7075-T6 Al Sheet	2.3 (0.090)	---	---	---	58.7 (53.4)	---	---
Single Layer 7075-T6 Al Sheet	1.3 (0.050)	---	---	---	66.6 (60.6)	---	---
Monolithic 7075-T651 Al Plate	Average Plate* 12.7 (0.50)	---	---	---	29 (26)	---	---
Diffusion Bonded 7075-T651 Al Laminate	2.3 (0.090)	11.9 (0.47)	1100 Al	0.10 (0.004)	52.5 (47.8)	90%	84%
Adhesively Bonded 7075-T6 Al Laminates	1.3 (0.050) 2.3 (0.090) 2.3 (0.090)	12.5 (0.49) 7.1 (0.28) 11.9 (0.47)	FM73M FM73M FM73M	0.13 (0.005) 0.13 (0.005) 0.13 (0.005)	66.1 (60.1) 55.6 (50.6) 53.4 (48.6)	99% 95% 91%	131% 95%** 87%

* Average plate value from reference 31.

** This value obtained from comparison to the 12.7 mm (0.50 in.) average plate.

*** K_c values determined from compact tension samples.

(2) The diffusion and adhesively bonded 7075-T651 and -T6 laminates having similar primary thicknesses exhibited similar toughnesses. The adhesively bonded laminate with the 1.3 mm (0.050 in.) primary thickness had higher toughness than comparable 2.3 mm (0.090 in.) primary thickness laminates.

(3) All laminates had significantly higher K_c values than monolithic Al alloys of the same thickness and heat treatment.

(4) The single layer Al sheet toughness was retained in all diffusion and adhesively bonded aluminum laminates, even in the thinnest interleaf diffusion bonded 7475 Al laminate.

In Figure 21, two crack growth resistance "R-Curves" are presented for the diffusion bonded 7475 Al/1100 Al laminate DA5 having two different heat treatments. These curves illustrate the greater damage tolerance available in the -T7651 condition compared to the -T651 condition in the 7475 Al laminate. It can be seen that while the -T7651 condition gives a little higher K_c value, the total subcritical crack growth to fracture is quite a bit greater. Similar curves are presented in Figure 22 showing the effects of bonding process on crack growth resistances of both 7475-T761 Al and 7075-T6 Al. It may be noted that in each case the diffusion bonded laminates exhibit considerably greater (on the order of 100%) subcritical crack growth before failure compared to the similarly treated adhesively bonded laminates. This one factor could prove to be very important in the determination and selection of bonding procedures to be used in damage tolerant laminate design giving metal/metal laminates a distinct advantage over adhesively bonded laminates.

Diffusion Bonded Ti-6Al-4V/CPTi Laminate Fracture Results. The fracture toughness values for the diffusion bonded Ti-6Al-4V/CPTi laminate DT2 are given in Table 24. These fracture results were determined on the as-bonded laminate material which was fabricated from the primary alloy Ti-6Al-4V in the recrystallization annealed condition. All tests were conducted with compact tension samples (Figure 4).

Table 25 shows comparative average critical fracture toughness values, K_c, for single layer Ti-6Al-4V sheet and plate and diffusion bonded Ti-6Al-4V/CPTi in the same recrystallization annealed heat treatment conditions. It can be seen that all three materials have essentially the same K_c values as would be expected, if no thickness effects were present. Some crack growth resistance

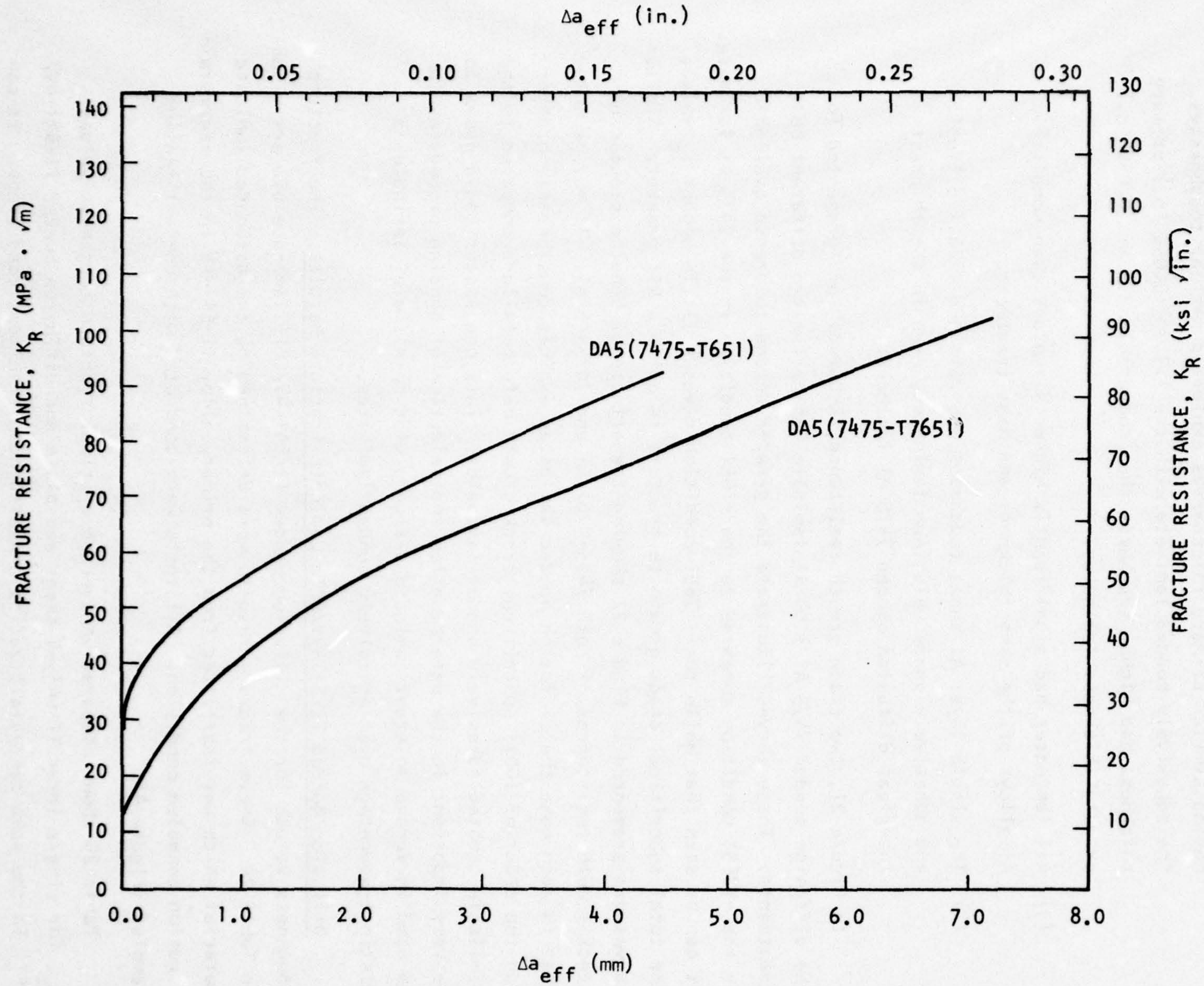


FIGURE 21. CRACK GROWTH RESISTANCE CURVES FOR DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DA5 IN THE -T651 AND -T7651 CONDITIONS.

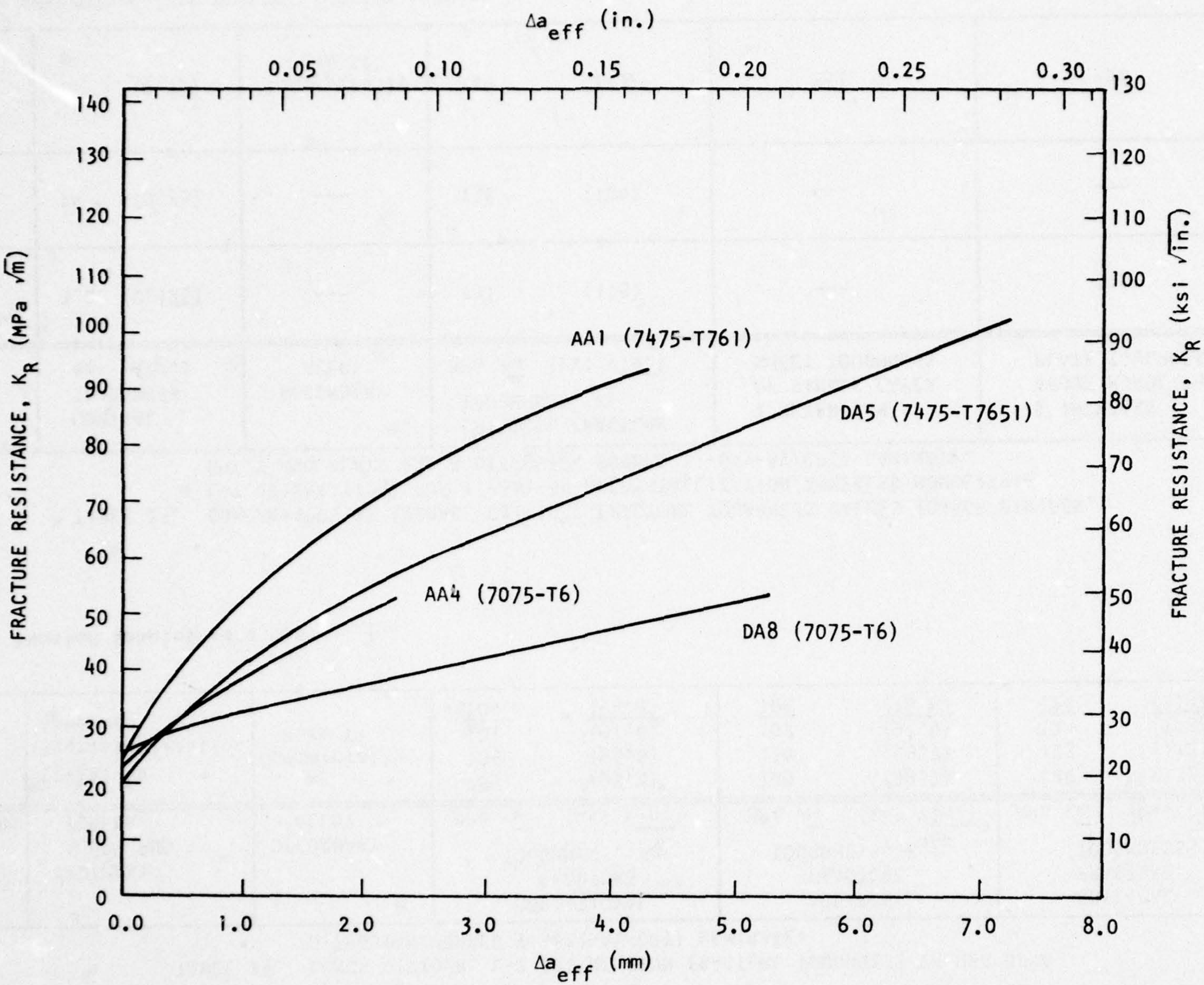


FIGURE 22. CRACK GROWTH RESISTANCE CURVES FOR DIFFUSION AND ADHESIVELY BONDED 7475 Al AND 7075 Al LAMINATES DA5, DA8, AA1 AND AA4.

TABLE 24. CRACK DIVIDER, L-T ORIENTATION FRACTURE TOUGHNESS VALUES OF A DIFFUSION BONDED Ti-6Al-4V/CPTi LAMINATE.

LAMINATE DESIGNATION	PRIMARY ALLOY AND TEMPER	SECONDARY ALLOY	CONDITIONAL FRACTURE TOUGHNESS, K_Q MPa $\sqrt{m}$	(ksi $\sqrt{in.}$)	APPARENT FRACTURE TOUGHNESS, K_{app} MPa $\sqrt{m}$	(ksi $\sqrt{in.}$)	CRITICAL FRACTURE TOUGHNESS, K_c MPa $\sqrt{m}$	(ksi $\sqrt{in.}$)
DT2	Ti-6Al-4V Recrystallization Annealed	Commercially Pure Ti	105	(95.8)	109	(99.2)	124	(113)
			105	(95.6)	110	(99.7)	123	(112)
			101	(91.6)	107	(97.4)	124	(113)
			Avg 104	(94.3)	109	(98.8)	124	(113)

* Compact Tension Samples were used.

TABLE 25. COMPARISONS OF AVERAGE CRITICAL FRACTURE TOUGHNESS VALUES (CRACK DIVIDER, L-T ORIENTATION) FOR Ti-6Al-4V RECRYSTALLIZATION ANNEALED MONOLITHIC SHEET AND PLATE AND A DIFFUSION BONDED Ti-6Al-4V/CPTi LAMINATE.

Material	NOMINAL THICKNESS mm	(in.)	SECONDARY ALLOY	CRITICAL FRACTURE TOUGHNESS, K_c MPa $\sqrt{m}$	(ksi $\sqrt{in.}$)	% RETENTION OF SINGLE LAYER SHEET TOUGHNESS	% INCREASE ABOVE MONOLITHIC PLATE TOUGHNESS
Single Layer Ti-6Al-4V Sheet	3.2	(0.125)	---	131	(119)	---	---
Monolithic Ti-6Al-4V Plate	14	(0.55)	---	136	(124)	---	---
Diffusion Bonded Ti-6Al-4V Laminate	16	(0.65)	Commercially Pure Ti	124	(113)	95%	-9%

* K_c values determined from compact tension samples.

curves for these three materials are presented in Figure 23. In these curves the laminate and the sheet materials exhibit essentially the same behavior but they are both considerably inferior to the plate material. This result would be very distressing were it not for the fact that the plate and sheet materials were from different heats and had somewhat different chemistries (see Table 4). It is speculated that these differences could be sufficient to produce the variations in subcritical crack growth behavior observed for the plate and sheet materials.

Diffusion Bonded Ultrahigh Carbon Steel/Iron Laminate Fracture Results. The fracture toughness of one diffusion bonded UHC Steel/Iron laminate sample was evaluated in the as-bonded condition. The composition of this UHC steel differed from that previously reported in Table 5 for the 2.8 mm (0.11 in.) sheet material. (The chemical composition of UHC steel in the laminate was approximately 1.6% C, 1% Mn, 0.07% Si and 0.52% Nb.) This laminate had been bonded as described in Section 2.2 at 650°C (1200°F) for twelve hours and accordingly should be considered to be well annealed. The fracture toughness test was performed using a small compact tension sample which had dimensions equal in every case to one half those given for the standard sample described in Figure 4. In Table 26 the results of this test are compared to those obtained for similar small monolithic sheet compact tension samples of the composition reported in Table 5. The monolithic sheet samples were evaluated in two different heat treated conditions: As-received and annealed. The as-received material had been solution treated at 1100°C (2012°F) for 1.75 hours, rolled from 42.6 mm (6.68 in.) to 14 mm (0.55 in.) in 27 passes during cooling from 1100°C (2012°F) to approximately 600°C (1112°F) and isothermally rolled at 650°C (1200°F) from 14 mm (0.55 in.) to 2.8 mm (0.11 in.). The annealed sample had an additional 20 minutes at 650°C (1200°F) in argon followed by air cooling. The laminate exhibited poorer fracture toughness properties than the sheet materials but compositional and thickness differences between the UHC steels used really preclude direct comparisons being made. Also, approximately 27% of the cross section of the laminate is weak iron and this could be expected to significantly affect the toughness of the laminate further rendering comparisons to the sheet UHC steel questionable.

Failure in Laminates. Failure surfaces of selected laminate and monolithic compact tension samples are given in Figures 24 through 27. In contrast

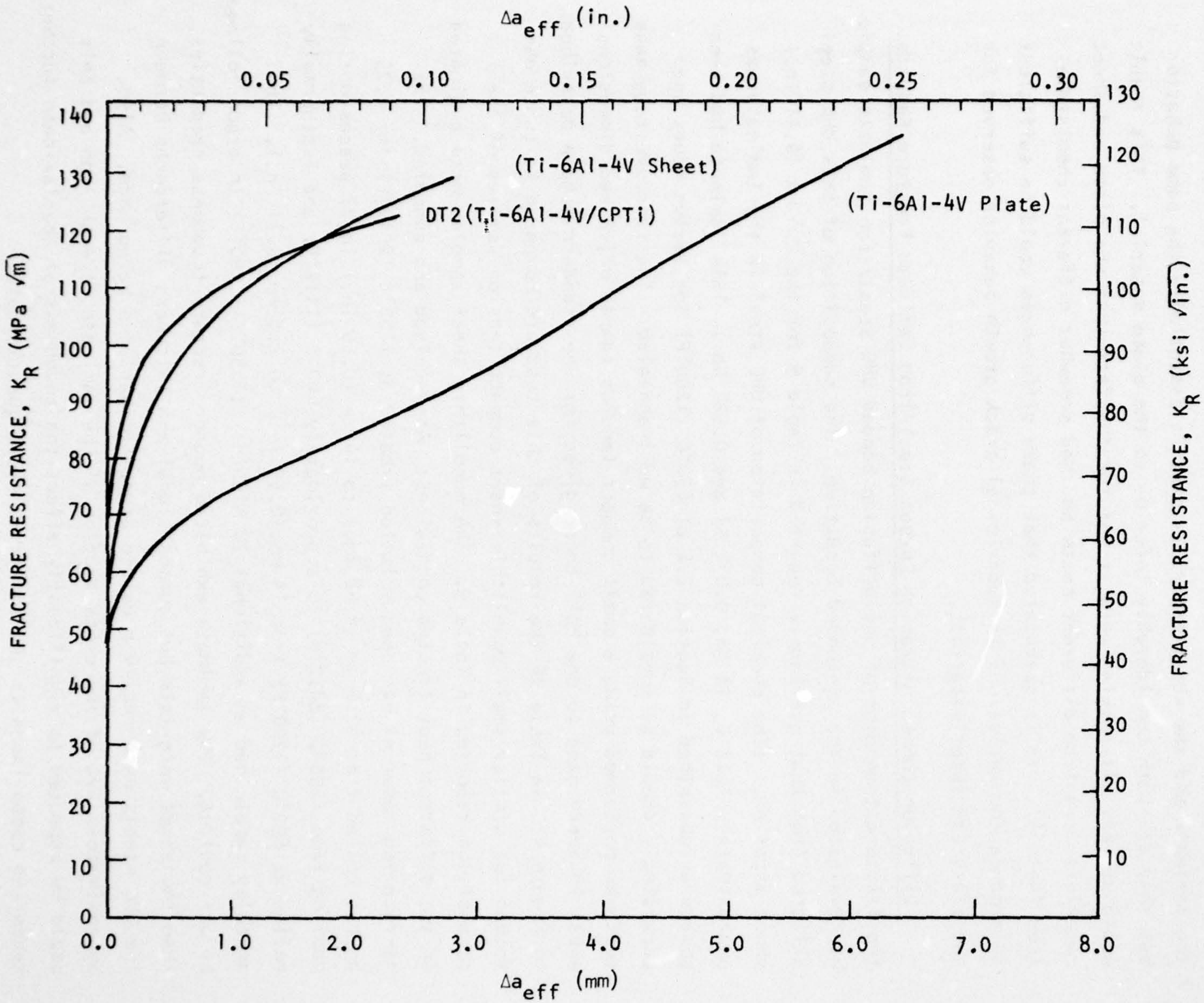


FIGURE 23. CRACK GROWTH RESISTANCE CURVES FOR MONOLITHIC Ti-6Al-4V SHEET AND PLATE AND A DIFFUSION BONDED Ti-6Al-4V-4V/CPTi LAMINATE DT2.

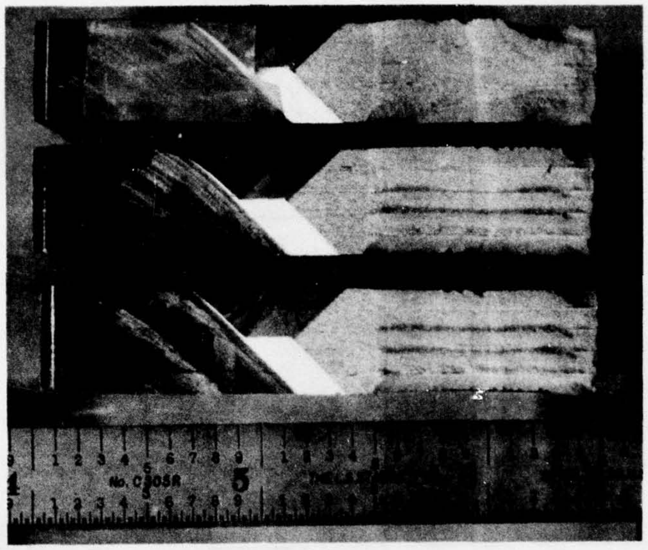
TABLE 26. FRACTURE TOUGHNESS PROPERTIES (CRACK DIVIDER, L-T ORIENTATION) FOR ULTRAHIGH CARBON STEEL SHEET AND A DIFFUSION BONDED UHC STEEL/IRON LAMINATE.

MATERIAL AND TEMPER	NOMINAL THICKNESS mm (in.)	SECONDARY ALLOY	CONDITIONAL FRACTURE TOUGHNESS, K_Q		APPARENT FRACTURE TOUGHNESS, K_{app}		CRITICAL FRACTURE TOUGHNESS, K_c	
			MPa $\sqrt{m}$	(ksi $\sqrt{in.}$)	MPa $\sqrt{m}$	(ksi $\sqrt{in.}$)	MPa $\sqrt{m}$	(ksi $\sqrt{in.}$)
UHC Steel, As-Received	2.8 (0.11)	---	82.6	(75.2)	119	(108)	137	(125)
UHC Steel, Annealed	2.8 (0.11)	---	58.8	(53.5)	101	(92.3)	162	(147)
Diffusion Bonded UHC Steel Laminate, As-Bonded	4.5 (0.18)	Iron	38.9	(35.4)	70.3	(64.0)	126	(115)

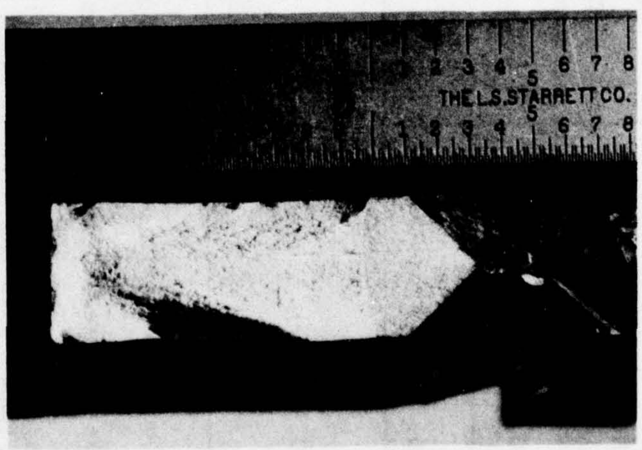
* Small compact tension samples were used which had dimension equal to one-half those given in Figure 4.

** UHC steel in laminate differed in composition from that of the UHC steel sheet (see text).

*** UHC steel primary layers in laminate were nominally 0.80 mm (0.032 in.) thick and secondary iron interleaves were nominally 0.40 mm (0.016 in.) thick.

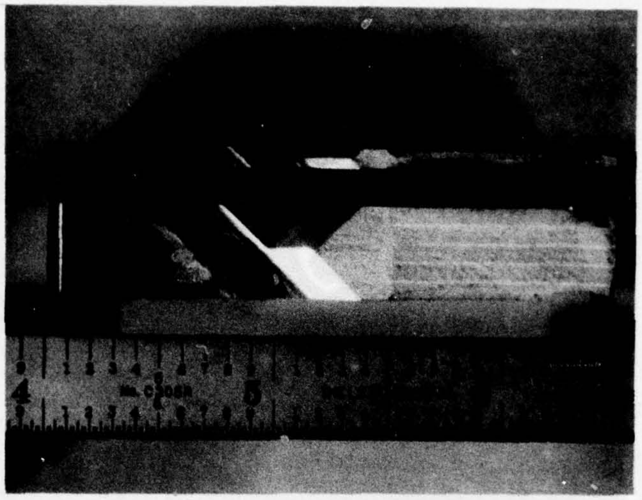


(a)

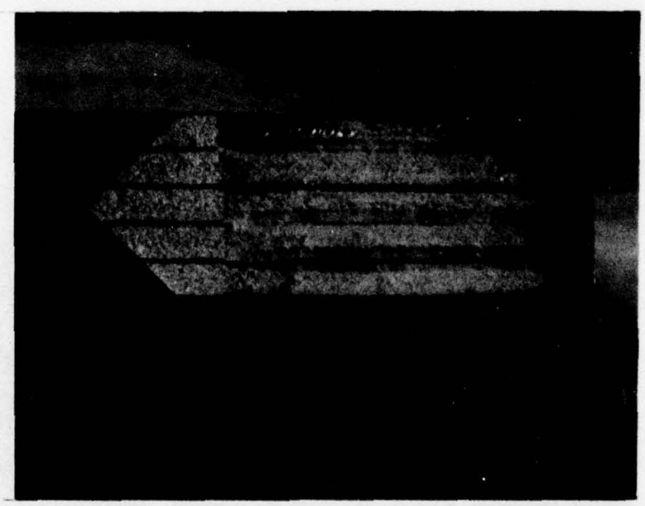


(b)

FIGURE 24. FAILURE SURFACES OF DIFFUSION BONDED 7475Al LAMINATE:
(a) TOP TO BOTTOM: DA4, DA5, DA6.
(b) CLOSER VIEW OF DA4 SHOWING RELATIVELY FLAT FRACTURE SURFACE.

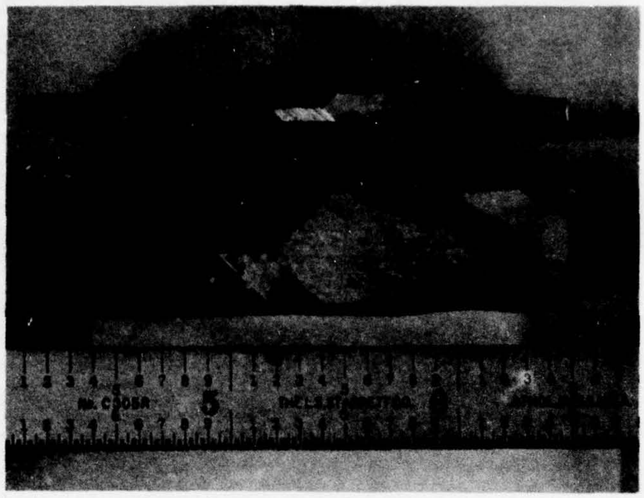


(a)

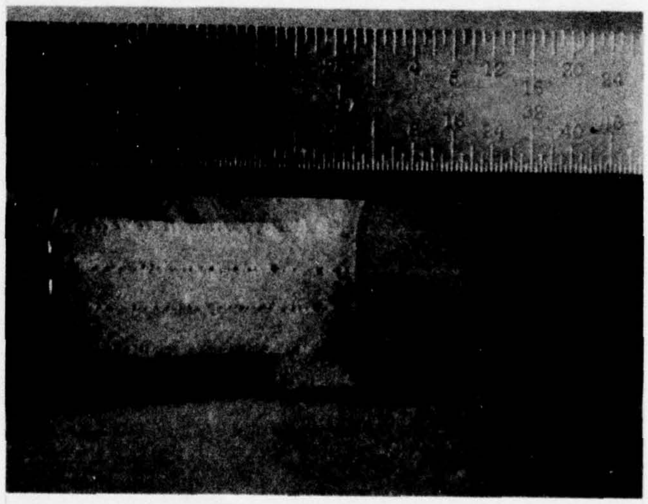


(b)

FIGURE 25. FAILURE SURFACES OF 7075 Al SHEET AND LAMINATE CRACK DIVIDER CT SPECIMENS: (a) SHEET AND DIFFUSION BONDED LAMINATE DA8; (b) ADHESIVELY BONDED LAMINATE AA4.



(a)



(b)

FIGURE 26. FAILURE SURFACES OF MONOLITHIC Ti-6Al-4V SHEET, PLATE, AND LAMINATE CRACK DIVIDER CT SPECIMENS: (a) SHEET AND PLATE; (b) DIFFUSION BONDED LAMINATE DT2.

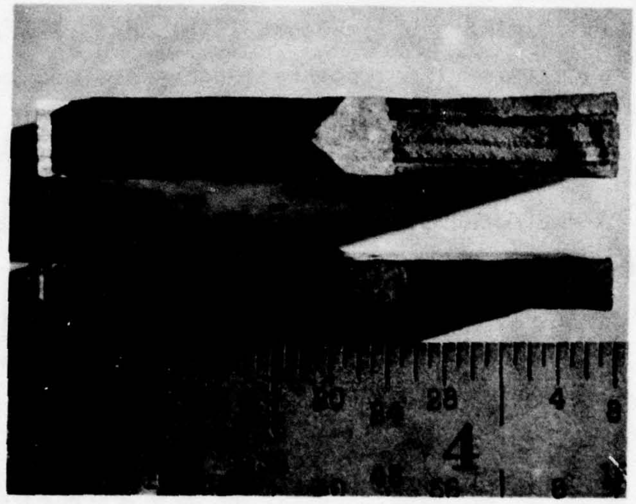


FIGURE 27. FAILURE SURFACES OF UHC STEEL LAMINATE AND SHEET CRACK DIVIDER CT SPECIMENS: (UPPER) DIFFUSION BONDED LAMINATE DUHC 1; (LOWER) SHEET.

to the observation of a previous report,[21] not all laminate specimens exhibited plane stress (or slant) failure surfaces of the individual primary layers. In particular, the diffusion bonded 7475 Al/1100 Al laminate DA4, Figure 24(b), which had the thinnest interleaf thickness 0.05 mm (0.002 in.) and the diffusion bonded Ti-6Al-4V/CPTi laminate DT2, Figure 26(b), had relatively flat fracture surfaces. In spite of this, the fracture toughnesses of these samples were essentially the same as those of the comparable individual sheet samples from which these laminates were made.

Fractography of selected diffusion bonded samples was conducted using scanning electron fractography. Fractographs showing the "cohesive" failures observed in every case are given in Figures 28 through 33. As mentioned earlier in this report, a major accomplishment was the achievement of these desirable cohesive failures in the diffusion bonded Al/Al laminates for they are indicative of the excellent bonding obtained. The resistance to "adhesive" delaminations at the bond plane interfaces is necessary to the strengthening heat treatments which must be performed subsequent to bonding. The "dimpled" rupture in the interleaves in each case observed indicates the good ductility retained in the interleaf metals which helped insure against delamination during the severe quenching used in heat treatments.

3.5.2 Fracture of Crack Arrest Metal/Metal Laminates

The crack arresting properties of metal/metal laminates are as attractive as the fracture toughness properties of crack divider laminates, if not more so. Three point bend fracture specimens of L-S, crack arrest orientation (Figure 6) were used to document the crack arrest properties of two of the diffusion bonded Al/Al laminates and the diffusion bonded Ti/Ti laminate. The diffusion bonded laminate DA5 was evaluated in two different heat treatment conditions. The results of these evaluations are given in Table 27. In every case for the Al/Al laminates, crack arrest occurred at the first interleaf under rising loading fracture conditions. In the Ti/Ti laminates, crack arrest did not occur. Typically these three point bend specimens had notches of 1.3 mm (0.050 in.) depth with fatigue precracks of 0.25 mm (0.010 in.) length. In the Al specimens tested under rising load the following sequence was noted in each case:

(1) The load increased until the primary layer containing the crack suffered catastrophic failure.

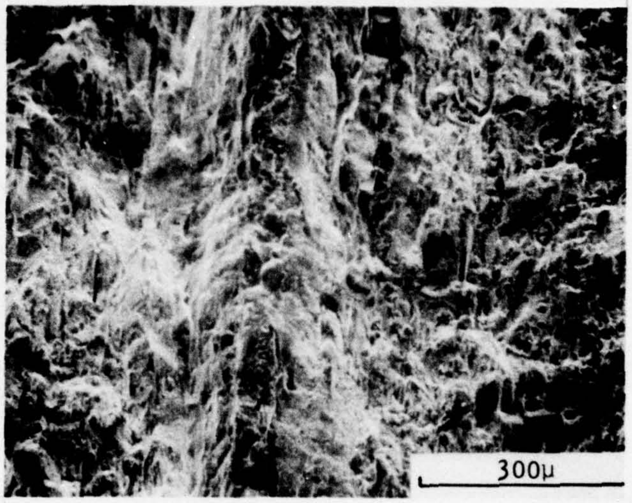


FIGURE 28. FRACTOGRAPH OF DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DA4 CT FAILURE SURFACE SHOWING INTERLEAF REGION.

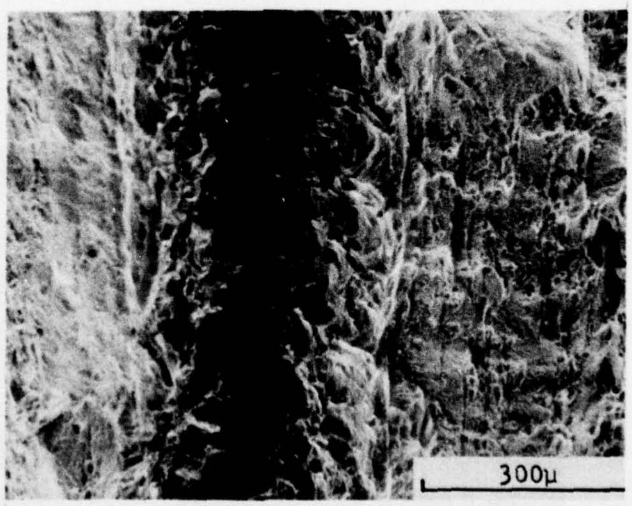


FIGURE 29. FRACTOGRAPH OF DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DA5 CT FAILURE SURFACE SHOWING INTERLEAF REGION.

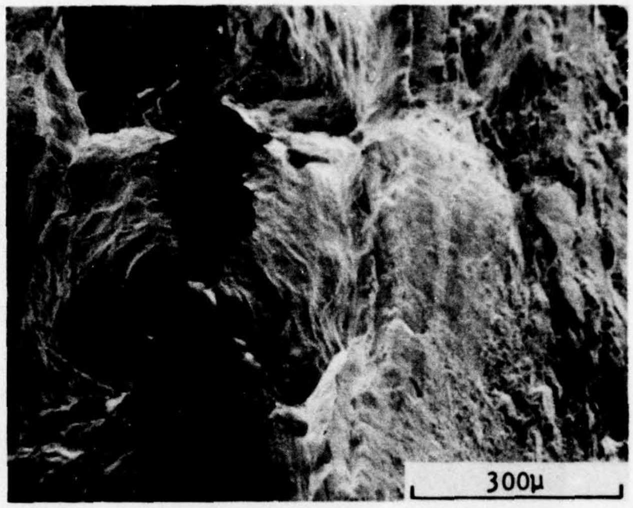


FIGURE 30. FRACTOGRAPH OF DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DA6 CT FAILURE SURFACE SHOWING INTERLEAF REGION.

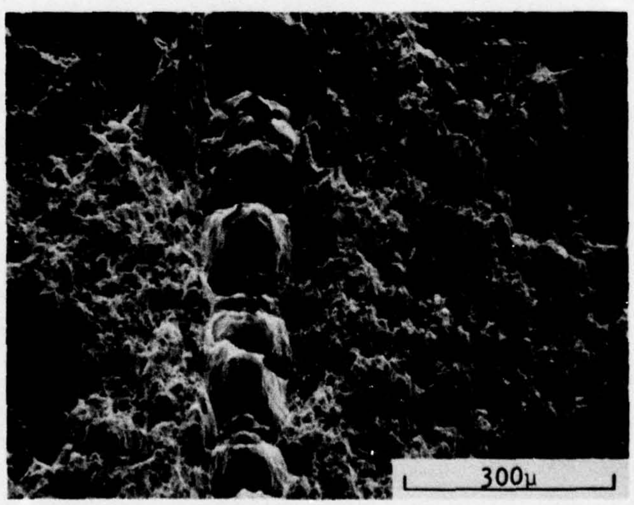


FIGURE 31. FRACTOGRAPH OF DIFFUSION BONDED 7075 Al/1100 Al LAMINATE DA8 CT FAILURE SURFACE SHOWING INTERLEAF REGION.

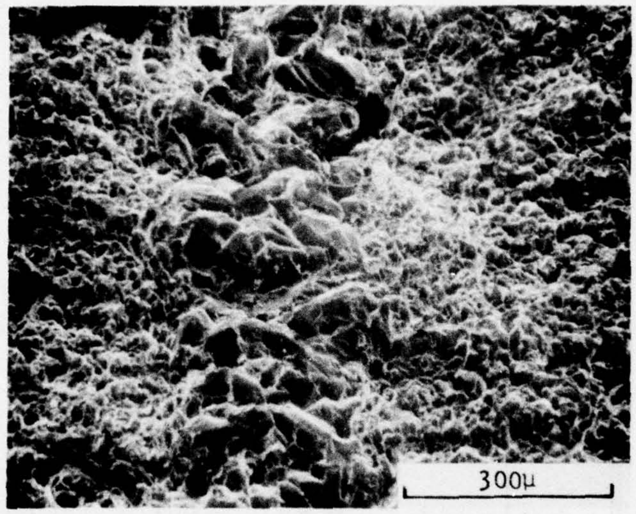


FIGURE 32. FRACTOGRAPH OF DIFFUSION BONDED Ti-6Al-4V/CPTi LAMINATE DT2 CT FAILURE SURFACE SHOWING INTERLEAF REGION.

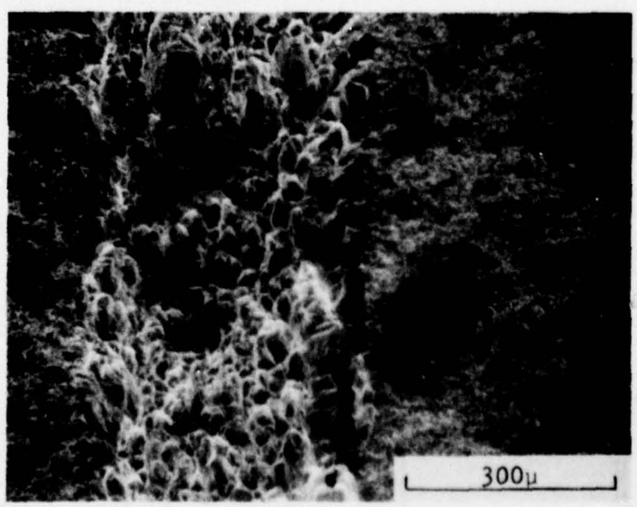


FIGURE 33. FRACTOGRAPH OF DIFFUSION BONDED UHC STEEL/IRON LAMINATE DUHC 1 CT FAILURE SURFACE SHOWING INTERLEAF REGION.

TABLE 27. CRACK ARREST, L-S ORIENTATION THREE POINT BEND FRACTURE TEST RESULTS FOR SELECTED DIFFUSION BONDED LAMINATES

LAMINATE DESIGNATION	PRIMARY/ SECONDARY ALLOYS	HEAT TREATMENT	TEST NUMBER	CRACK ARREST @ 1st INTERLEAF
DA5	7475 Al/1100 Al	-T651	1	Yes
			2	Yes
			3	Yes
		-T7651	1	Yes
			2	Yes.
			3	Yes
DA7	7475 Al/6061 Al	-T651	1	Yes
			2	Yes
			3	Yes
DT2	Ti-6Al-4V/CPTi	As-Bonded	1	No
			2	No
			3	No

(2) The crack did not propagate beyond the first secondary alloy interleaf that it encountered.

(3) No delaminations at other interleaves were observed even after general yielding of the specimens.

In the Ti/Ti specimens, cracks propagated through every interleaf under rising load conditions producing failures similar to those in the monolithic plate three point bend specimens. Further examination of the bonding conditions and/or interleaf materials used in the all Ti laminates will be necessary to overcome this crack arrest deficiency.

One test was run on the diffusion bonded laminate DA5 to evaluate its crack arrest characteristics. Because of the significant diffusion of alloying elements into the thin 0.05 mm (0.002 in.) 1100 Al interleaf and its consequent hardening (see Sections 3.2.2 and 3.3), it was anticipated that crack arrest capability in this material would be limited. Indeed, it was found that under fatigue loading (a condition in which there is a small cyclic plastic zone at the crack tip) a propagating crack could pass through the bond plane interfaces without arrest. A crack was grown by this means into the third primary layer at which time a rising load was applied (a condition which produces a considerably larger plastic zone at the crack tip). Immediate crack arrest occurred at the next interleaf. This sample is shown in Figure 34 (lower). One of the rising load fracture samples, DA5, with a thicker interleaf is also included in Figure 34 (upper). It was concluded from this test that the thinnest interleaf, the 0.05 mm (0.002 in.) 1100 Al, was only marginally too thin for the bonding and heat treating conditions used.

3.6 FATIGUE CRACK PROPAGATION WITH PERIODIC OVERLOADS

Compact tension specimens (Figure 4) were used to document the fatigue crack propagation rates in 7475-T761 Al sheet, 7475-T765 Al plate and roll bonded 7475 Al/1100 Al laminate RA4 under the influence of periodic overloads. These tests were conducted at room temperature at 10 Hz and an R ratio (ratio of minimum to maximum load) of 0.1 with overload ratios of 1.5 and 1.8 (the ratio of the overload to maximum load in the fatigue cycle). The overload ratios chosen and the use of single overloads with a subsequent specified number of fatigue cycles essentially follow the techniques of Chanani.[36] The experimental procedure was standardized to include four overloads with an

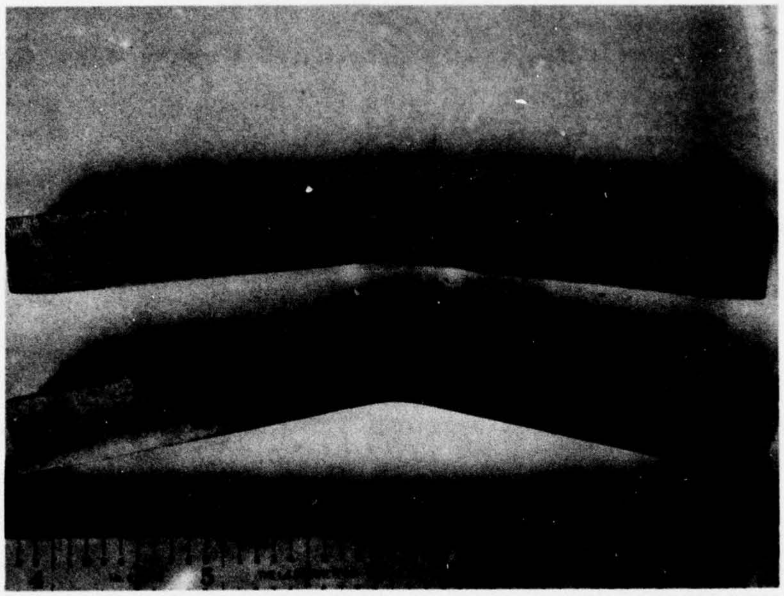
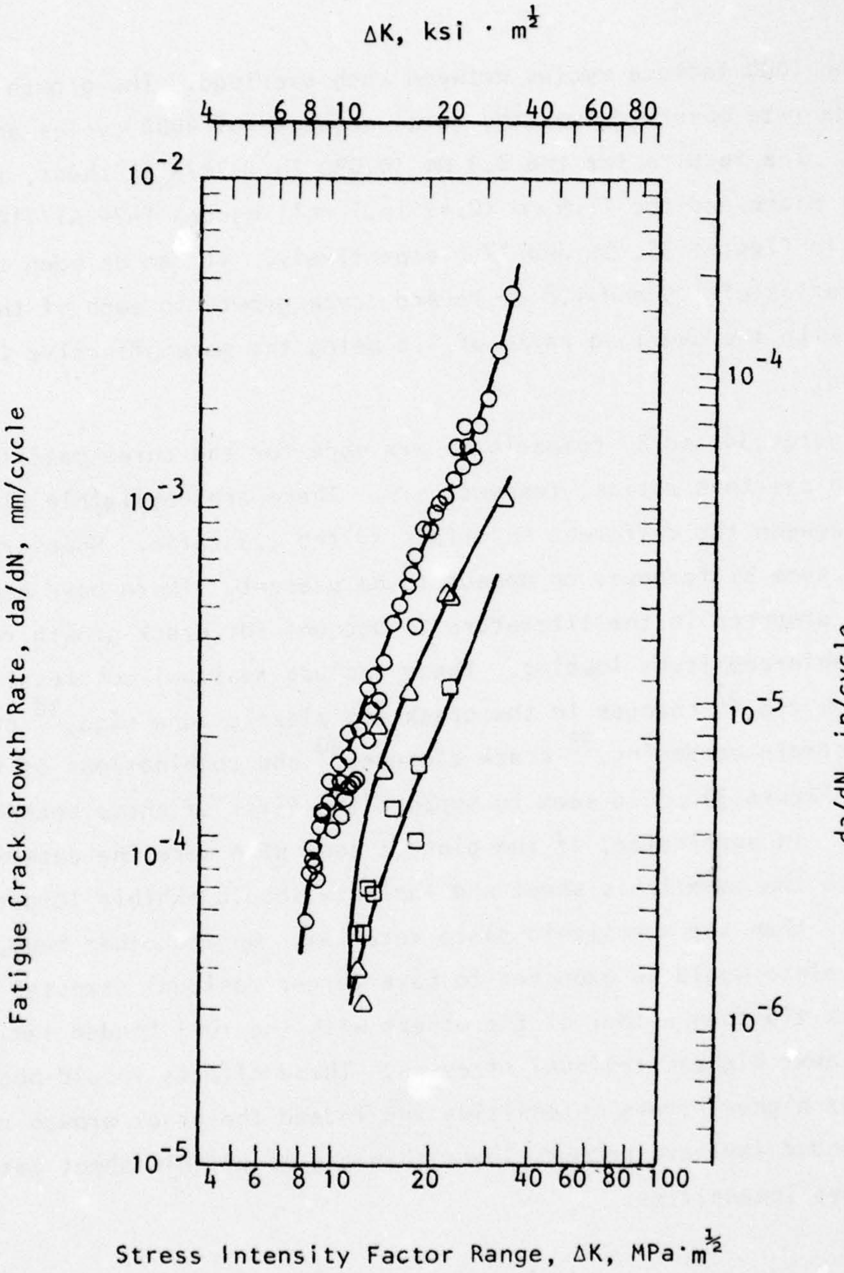


FIGURE 34. THREE POINT BEND FRACTURE SPECIMENS FOR DIFFUSION BONDED LAMINATES DA5 (UPPER) AND DA4 (LOWER). THE LOWER SAMPLE WAS FATIGUE CRACKED INTO THIRD PRIMARY LAYER (SEE TEXT).

intervening 1000 fatigue cycles between each overload. The growth rate was the average rate observed over the total sequence of 4000 cycles and four overloads. The results for the 2.3 mm (0.090 in.) 7475 Al sheet, the 11.9 mm (0.47 in.) plate and the 11.9 mm (0.47 in.) roll bonded 7475 Al/1100 Al laminate are given in Figures 35, 36 and 37, respectively. It can be seen that the overload ratios of 1.5 and 1.8 do retard crack growth in each of the materials evaluated with the overload ratio of 1.8 being the more effective in each case as expected.

In Figures 38 and 39 comparisons are made for the three materials at the 1.5 and 1.8 overload ratios, respectively. There are negligible differences observed between the different materials at the 1.5 ratio. However, at the 1.8 ratio, some differences do appear to be present. There have been several mechanisms proposed in the literature to account for crack growth retardation under variable-amplitude loading. These include residual compressive stresses at the crack tip,[37] changes in the crack tip plastic zone size,[38] crack blunting, strain hardening,[39] crack closure,[40] and combinations of these. The results of Figure 39 would seem to support the first of these mechanisms over the others. In particular, if the plastic zone size were the determining factor, both the monolithic sheet and laminate should exhibit larger retardation effects than the monolithic plate material. On the other hand, the monolithic plate would be expected to have larger residual stresses operative at the crack tip than either of the others with the roll bonded laminate supporting next highest residual stresses. These effects should become more important at higher stress intensities and indeed the crack growth rate for the roll bonded laminate becomes lower than the monolithic sheet material at higher stress intensities.

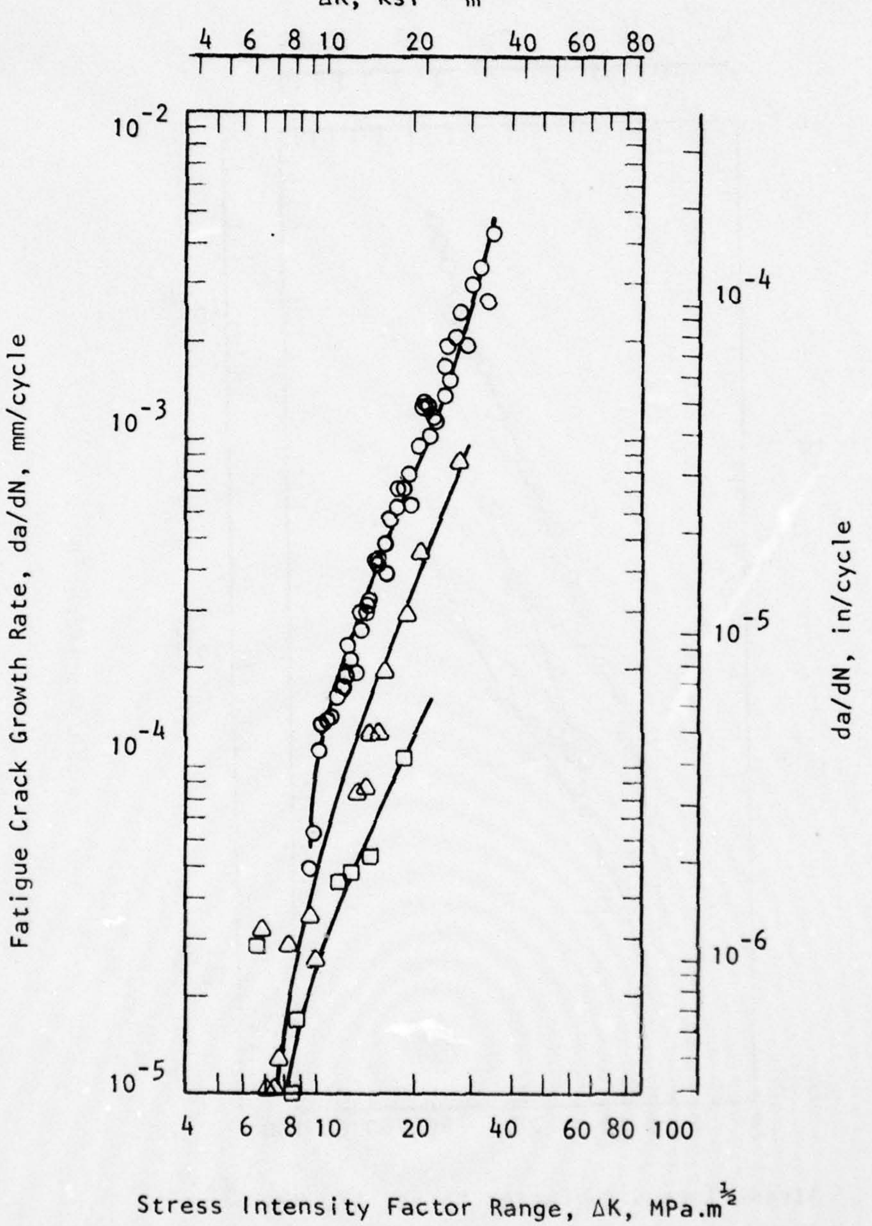


○ Monolithic 7475 Al Sheet with no overloads.

△ Monolithic 7475 Al Sheet with overloads of Ratio 1.5.

□ Monolithic 7475 Al Sheet with overloads of Ratio 1.8.

FIGURE 35. FATIGUE CRACK PROPAGATION RATES FOR 2.3 mm (0.090 in.) THICK 7475-T761 Al, L-T ORIENTATION, R = 0.1, f = 10 Hz.



○ Monolithic 7475 Al Plate with no Overloads.

△ Monolithic 7475 Al Plate with Overloads of Ratio 1.5.

□ Monolithic 7475 Al Plate with Overloads of Ratio 1.8.

FIGURE 36. FATIGUE CRACK PROPAGATION RATES FOR 11.9 mm (0.47 in.) THICK 7475-T7651, L-T ORIENTATION, R = 0.1, f = 10 Hz.

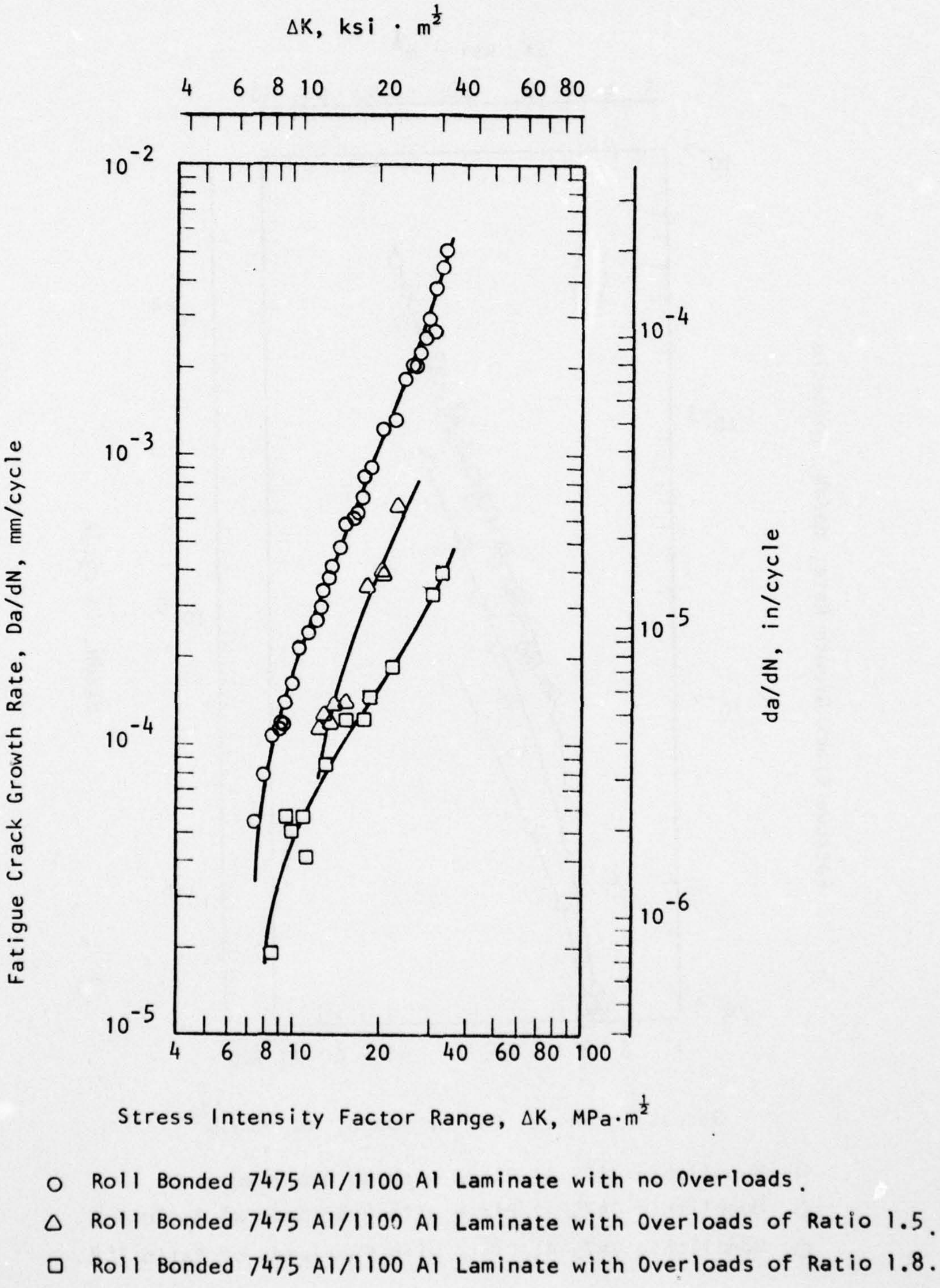


FIGURE 37. FATIGUE CRACK PROPAGATION RATES FOR 11.9 mm (0.47 in.) THICK ROLL BONDED LAMINATE RA4, CRACK DIVIDER, L-T ORIENTATION, R = 0.1, f = 10 Hz.

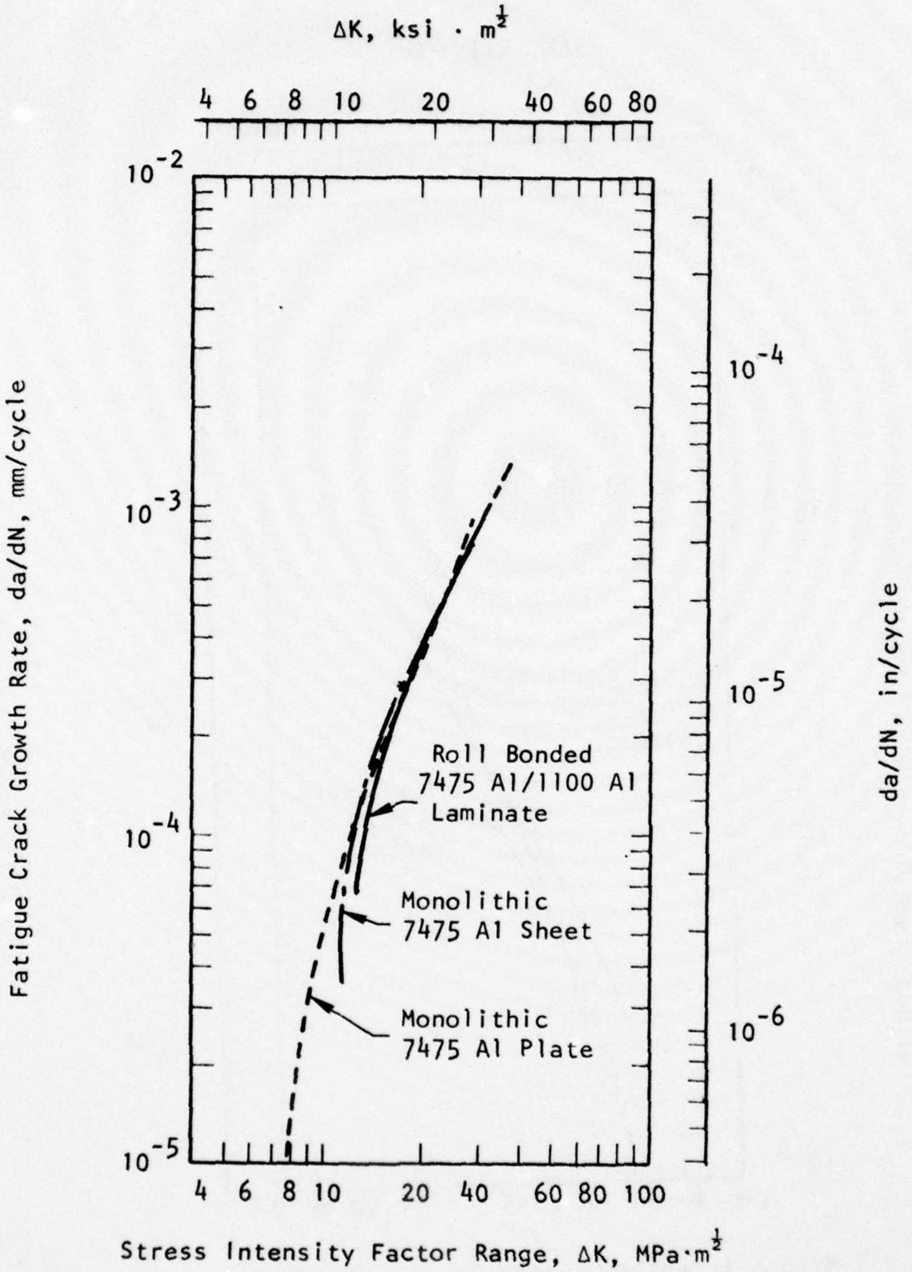


FIGURE 38. FATIGUE CRACK PROPAGATION RATES FOR MONOLITHIC 7475-T651,-T7651 Al SHEET AND PLATE AND ROLL BONDED RA4, CRACK DIVIDER, L-T ORIENTATION, OVERLOAD RATIO = 1.5.

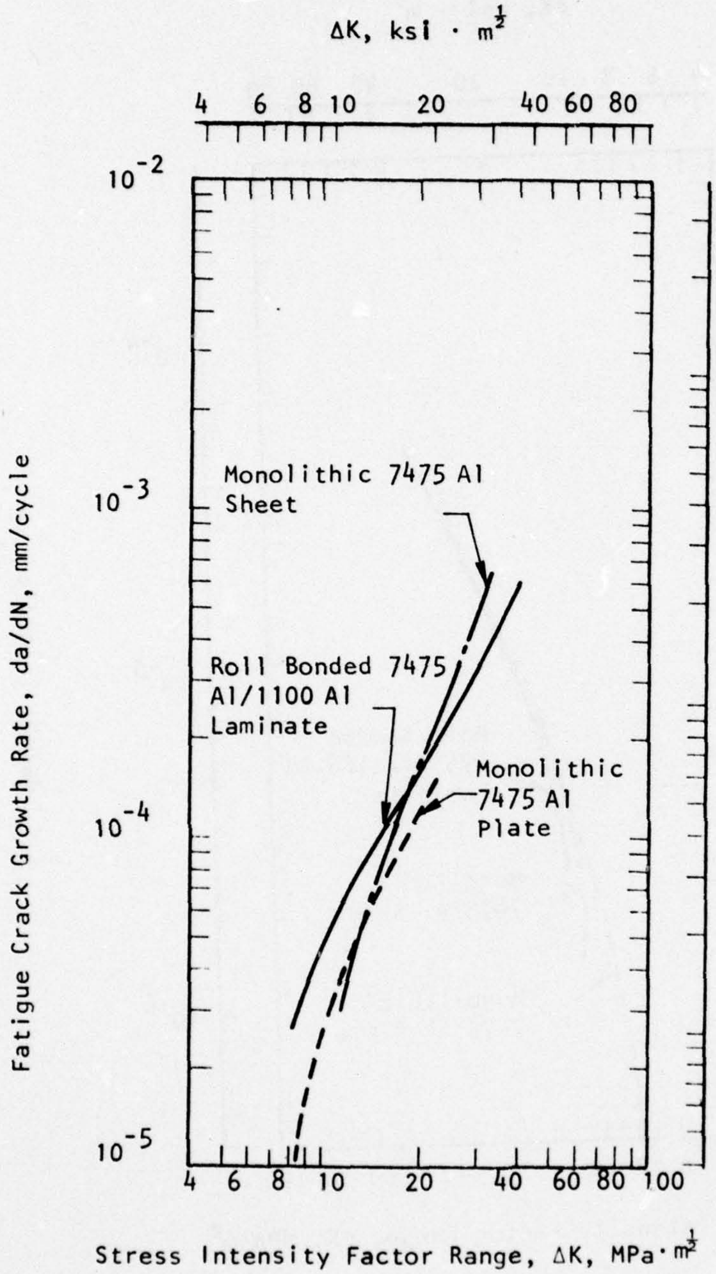


FIGURE 39. FATIGUE CRACK PROPAGATION RATES FOR MONOLITHIC 7475-T651, -T7651 Al SHEET AND PLATE AND ROLL BONDED, CRACK DIVIDER, L-T ORIENTATION, OVERLOAD RATIO = 1.8.

4.0 SUMMARY AND CONCLUSIONS

An experimental investigation of Aluminum/Aluminum, Titanium/Titanium, Ultrahigh Carbon Steel/Iron and Aluminum/Epoxy laminates was conducted. The effects of changes in processing variables for enhanced diffusion bonding in all aluminum and all-titanium laminates were examined by optical microscopy, electron beam microanalysis, microhardness and bond plane shear testing. Primary sheet and secondary interleaf thicknesses were varied along with heat treatments of the primary alloys in selected laminates. The effects of diffusion and adhesive bonding, thicknesses of primary and secondary materials, and heat treatments on the fracture behavior of the laminates were determined by fracture mechanics testing, optical and scanning electron microscopy. The effects of periodic overloads on the fatigue crack propagation rates in monolithic aluminum sheet and plate and a roll bonded aluminum laminate were also examined.

The specific laminate configurations that were fabricated and evaluated included the following systems:

Diffusion bonded laminates	7475 Al/1100 Al Alloys 7475 Al/6061 Al Alloys 7075 Al/1100 Al Alloys 7075 Al/7072 Al Alloys Ti-6Al-4V/CPTi Alloys UHC Steel/Iron Alloys
Adhesively bonded laminates	7475 Al/FM73M Alloy/Epoxy 7075 Al/FM73M Alloy/Epoxy
Roll bonded laminate	7475 Al/1100 Al Alloys

For the most part, these laminates consisted of five layers of primary metal [e.g., 2.3 mm (0.090 in.) 7475 Al] interleaved with four layers of thin secondary material [e.g., 0.3 mm (0.005 in.) 1100 Al]. The following conclusions were made from this program:

<u>General Metal Laminate Properties</u>

1. The principle requirement for attaining high fracture toughness in laminates is that the primary metal layers in a laminate fail individually under plane stress conditions. The key factor controlling plane stress failure of the primary layers is that failure occurs

at the primary/secondary bond prior to development of a plane strain condition through the thickness of the laminate. In metal/metal laminates, this means that the interleaf metal strength must be less than the primary metal strength.

2. Toughness improvements of up to 100% over monolithic plate plane strain values were achieved in the diffusion bonded metal/metal and adhesively bonded metal/epoxy laminate systems evaluated. The average K_c values were measured to be 88% to 115% of the K_c values for the single layer primary alloy sheets of approximately the same thickness as the primary layer in the laminates.

3. The crack divider fracture toughness of an appropriately bonded laminate depends ultimately on the toughness of the individual primary layers comprising the laminate. By taking advantage of the K_c versus thickness relationships, laminates of maximum damage tolerance may be built up from sheets to meet specific design criteria.

4. Diffusion bonding can be used for a variety of metal/metal systems to fabricate high damage tolerance laminates. Surface cleaning procedures prior to bonding, the bonding conditions employed, and the interleaf thicknesses all are important to the properties of the laminates produced.

5. The high interfacial bond plane shear strengths [from 103 MPa (15 ksi) to 213 MPa (31 ksi) in Al/Al laminates and 454 MPa (66 ksi) in a Ti/Ti laminate] allow strengthening heat treatments and conventional aircraft fabrication procedures to be employed. Such high bond plane shear strengths give these damage tolerant metal/metal laminates a much more isotropic character than comparable adhesively bonded laminates.

<u>Aluminum/Aluminum and Aluminum/Epoxy Laminate Properties</u>

1. All the diffusion and adhesively bonded 7475 aluminum and 7075 aluminum laminates had considerably higher critical fracture toughness than comparable monolithic aluminum plate of similar thickness. Increases of 100% were typical. For example, a laminate of 7475

Al/1100 Al in the -T651 condition had a K_c of 92 MPa $\sqrt{m}$ (84 ksi $\sqrt{in.}$) compared to a K_c of 44 MPa $\sqrt{m}$ (40 ksi $\sqrt{in.}$) for monolithic plate.

2. Measurements of diffusion and microhardness profiles in the diffusion bonded laminates indicated that interleaves of 0.10mm (0.004 in.) and 0.25mm (0.010 in.) had chemical compositions that insured soft, ductile interleaves.

3. While secondary metal interleaves of 0.10mm (0.004 in.) or greater thickness were capable of crack arrest by cyclic delamination, the 0.05mm (0.002 in.) thick interleaf in the diffusion bonded laminate was marginally too thin; it could support crack arrest under rising loads but not under lower stress intensity fatigue conditions.

4. The diffusion bonded aluminum laminates exhibited a greater crack growth resistance in the crack divider, L-T orientation than comparable adhesively bonded laminates.

5. At an overload ratio of 1.5 in fatigue crack growth studies, the roll bonded laminate exhibited a retardation behavior very similar to that of comparable sheet and plate. At an overload ratio of 1.8, crack growth retardation was generally greater than at a ratio of 1.5, and the laminate's crack growth rate fell between those of the individual sheet and monolithic plate values.

6. Bond plane shear strengths ranging from 103 MPa (15 ksi) to 214 MPa (31 ksi) were observed for the diffusion bonded Al/Al laminates.

Titanium/Titanium Laminate Properties

1. Fracture toughnesses of the recrystallization annealed all titanium laminate and monolithic sheet and plate differed little. This is illustrative of a general principle that in lower strength, higher toughness heat treatment conditions, metals exhibit less pronounced thickness effects on toughness than they do in higher strength conditions. Lamination thus produces greater improvements in toughness for alloys when they are in high strength conditions.

2. Measurements of diffusion and microhardness profiles in the diffusion bonded laminate indicated that the interleaves of commercially pure Ti remained soft but the laminate in the recrystallization annealed condition was incapable of crack arrest.

3. Bond plane shear strengths of 455 MPa (66 ksi) were observed in the diffusion bonded titanium laminate.

Ultrahigh Carbon Steel/Iron Laminate Properties

1. Preliminary evaluations indicate that good fracture toughness properties may be obtained in the superplastically formable ultrahigh carbon steel sheet and diffusion bonded laminates of ultrahigh carbon steel and iron.

2. Strengthening heat treatments for the ultrahigh carbon steel need refinement and the effects of these treatments on fracture toughness properties of varying thickness of sheet remains to be done before full characterization of laminates made from the ultrahigh carbon steel can be performed.

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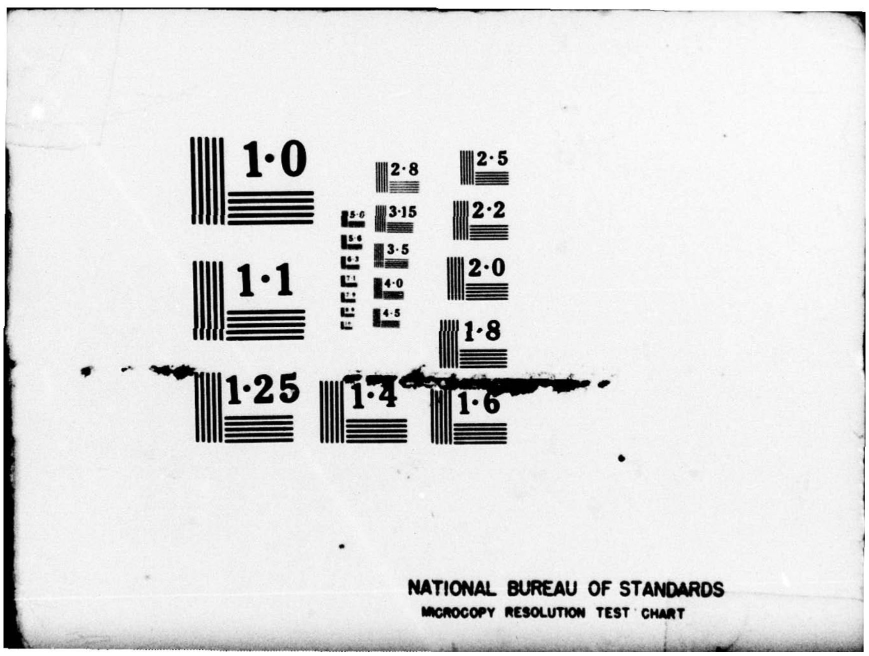
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